Nb_3Sn Quadrupole Development by LARP and application to the MQXF Design

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HL-LHC AUP DOE CD-2/3b Review – December 11th–13th; 2018

Presentation Outline

Purpose:

- Present the LARP key developments which are providing a technical basis to the HL-LHC IR Quadrupoles

Outline:

- LARP Organization and Goals
- Magnet Development Program
  - Potential and Challenges of Nb_3Sn Technology
  - R&D Phases and main achievements from fundamental technology demonstration to accelerator quality magnets
- Design solutions and criteria for MQXF resulting from the LARP experience

Introduction to the LARP Program

Organization:

- Started in 2003
- Progression from the US LHC Accelerator Research Project
- Collaboration of four national Labs: BNL, FNAL, LBNL, SLAC
- Funding level: $12-13M/year (from FY06)

Goals (as stated in the LARP proposal)

- Extend and improve the performance of LHC
  - Maximize scientific output in support of the experiments
- Maintain and develop US Labs capabilities
  - Prepare for a leadership role in future projects
- Research and training for US accelerator physicists
- Advance international collaboration on large accelerator projects

Magnet Program Overview

Motivation and goals:

- LHC luminosity upgrade studies pointing at the need for higher field, larger apertures and temperature margins → **Nb_3Sn IR Quadrupoles**
- LARP goal: *bridge from proof-of-principle tests to accelerator readiness*

Technology basis:

- Development of *high Jc Nb_3Sn wires in long lengths* by CDP and OST
- Development of *high field dipole models (up to 16 T)* by GARD programs

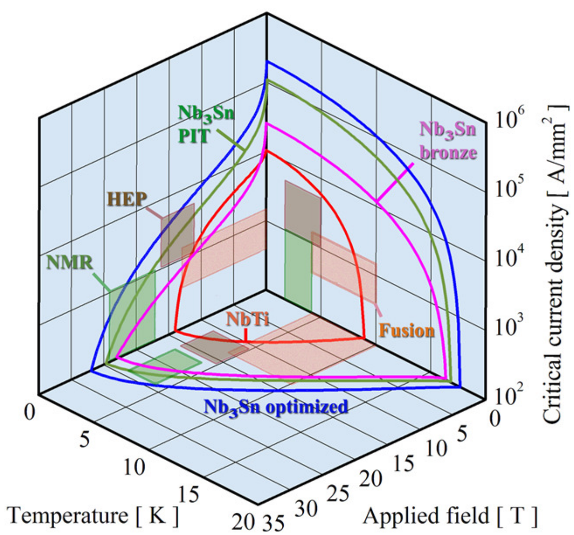
R&D Phases:

- 2005-2009: *consolidate and expand the technology foundation*
  - Conductor, coil fabrication, mechanical design, length scale-up
- 2009-2013: *accelerator quality and reliability in larger apertures*
  - Coil and structure alignment, electrical robustness, control of eddy currents
- From 2013: *final design and risk reduction for the project*
  - MQXF design and development (not covered in this talk)

Nb_3Sn technology: Potential and Challenges

Potential:

- Nb_3Sn critical temperature and field are about a factor of 2 larger than in NbTi
- Significantly expands the magnet design space: higher field and temperature margin



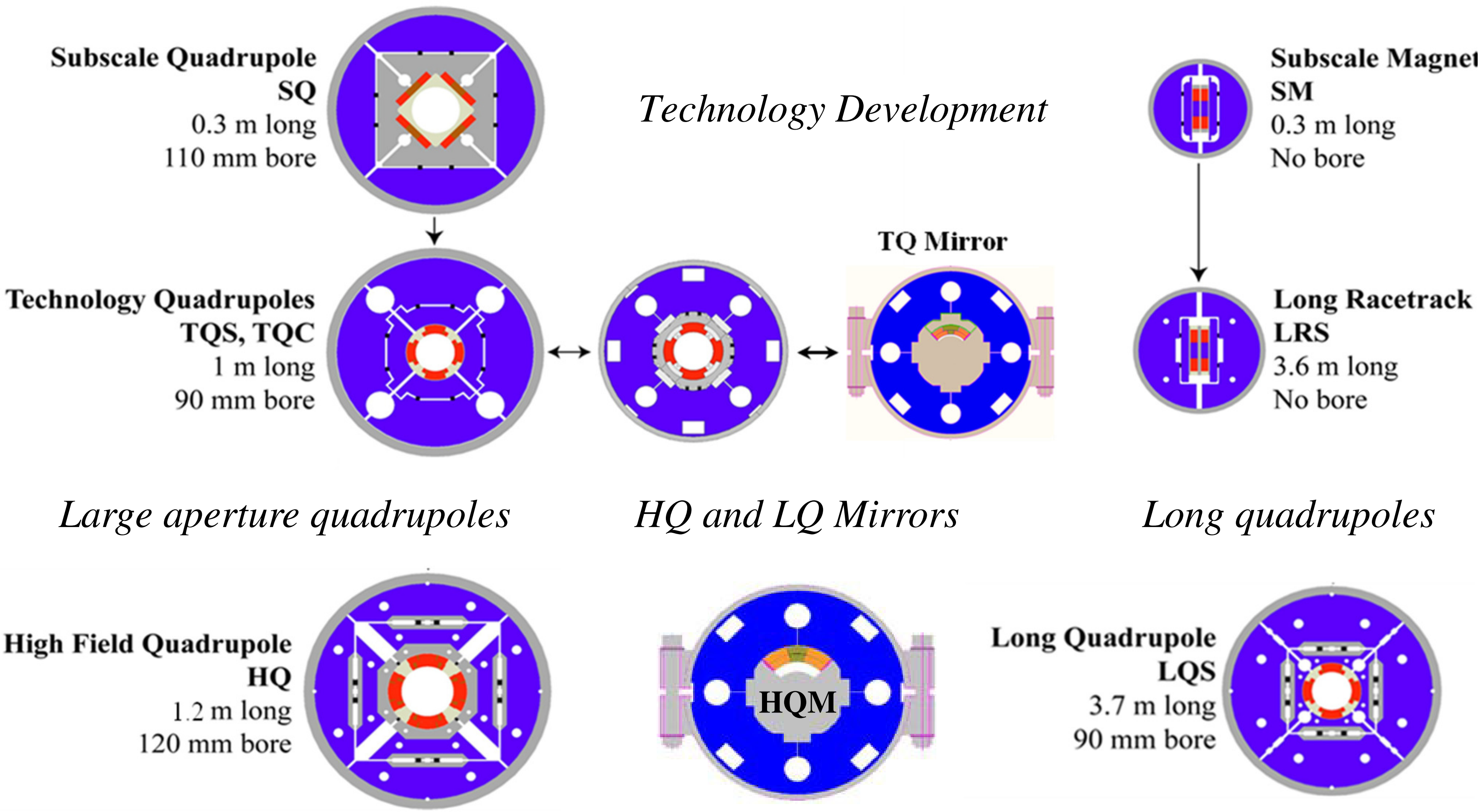
Challenges:

- Brittle material: severe damage in cabling/winding
  - React coils after winding
  - New materials (insulation, coil parts)
- High sensitivity to stress/strain:
  - Epoxy impregnation
  - New mechanical designs

Material	NbTi	Nb_3Sn
Dipole Limit	~ 10 T	~ 16 T
Reaction	N/A	~ 675^{0}C
Insulation	Polyimide	S/E Glass
Coil parts	G-10	Stainless
Irreversible Axial Strain	N/A	0.2-0.5 %
Transverse stress	N/A	~ 200 MPa

Model Magnet Development Chart

Started from simple configurations directed at basic technology studies and progressed to incorporate all requirements for operation in the accelerator



Fabrication and Test Database

Test facilities: LBNL (11 tests); BNL (2 tests); FNAL (26 tests); CERN (8 tests, funded by CERN)

Series	All new coils			Mix of new and retested coils				All coils previously tested (#)				
SQ**	SQ01	SQ02a						SQ01b	SQ02b	SQ02c		
LR	LRS01							LRS02				
TQC*	TQC01a			TQC02a				TQC01b	TQC02E	TQC02b	TQC03E	
TQS**	TQS01a	TQS02a	TQS03a	TQS01b	TQS02b			TQS01c	TQS02c	TQS03b	TQS03c	TQS03d
TQM*	TQM03a	TQM04a	TQM05					TQM01	TQM02	TQM03b	TQM03c	
LQM*	LQM01											
LQS	LQS01a	LQS02a	LQS03a					LQS01b				
HQM*	HQM01	HQM02	HQM04									
HQ	HQ01a			HQ01b	HQ01c	HQ01d	HQ02a	HQ01e	HQ01e2	HQ02a2	HQ02b	
LHQM	LHQM01											
Total	19			7				22				

(#): *includes coil exchanges with previously used coils, full reassembly with same coils, or pre-load adjustments*
(*): *includes contributions from FNAL GARD program*
(**): *includes contributions from LBNL GARD program*

- Demonstrated viability of reusing and replacing coils in multiple assemblies
- An important element of risk mitigation against defective coils in production

Technical Highlights

The following slides present selected highlights which are representative of the progress made by the LARP magnet program in key technical areas:

Technology Fundamentals:

- Selection of a uniform design and fabrication process for LARP coils
- Mechanical Design Comparison and Selection
- Pre-load optimization and stress limits
- Demonstration of magnet performance over a large number of cycles
- Scale-up to long coils and structures

Magnet production and operation in the accelerator:

- Optimization of coil and structure design, and fabrication process
- Introduction of cored cables to control eddy current effects
- Field quality measurements, analysis and correction
- Assessment of quench protection limits and CLIQ performance verification

Nb_3Sn strand used in LARP magnets

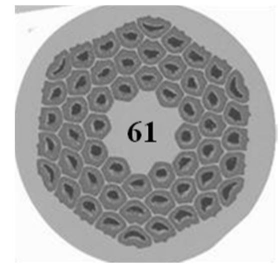
Wire architectures:

- OST-MJR (Modified Jelly Roll) 54/61: SQ, TQ01 (~2005-2006)
- OST-RRP (Rod Restack Process) 54/61: LR, TQ02, LQ01, HQ01 (2007-2011)
- OST-RRP 108/127: TQ03, LQ03, HQ02, HQ03 (2010-2015)

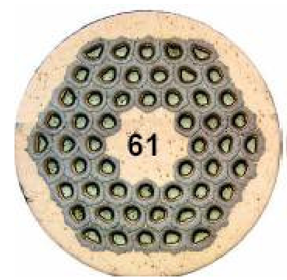
RRP 108/127 development and procurement:

- 90 kg of Ta ternary from CDP in 2008: 0.7 mm, TQS03
- 1300 kg of Ta ternary procured by LARP in 2009-2012, used in LQ (0.7 mm) and HQ (0.8 mm)
  - Required lower HT temperature (640-650 C) to meet RRR specs
- 90 kg of Ti ternary from CDP contract in 2009: used in HQ/LHQ (0.8 mm)
  - Achieves optimal J_c at a lower HT temperature
  - Improved piece length
- 410 kg of Ti ternary procured by LARP in 2012-13
  - Half of the billets used 5% reduced Sn for improved RRR

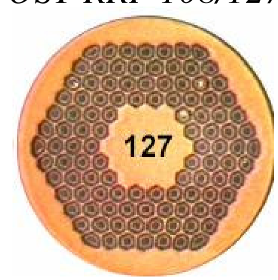
OST-MJR 54/61



OST-RRP 54/61



OST-RRP 108/127



Strain dependence in RRP wires

- Detailed studies of strain dependence in RRP wires by Cheggour et al. can be summarized as follows:
  - The intrinsic irreversible strain limit $\varepsilon_{irr,0}$ has a strong dependence on the temperature θ of the last stage of the heat treatment
  - Abrupt transition in $\varepsilon_{irr,0}$ from ~0 to 0.4% in a range of <25 ˚C (strain irreversibility cliff)
  - New*: this behavior applies to both Ta and Ti doped wires, but critical θ is 10-12 ˚C higher in Ta doped wires, further constraining the heat treatment optimization
- Ti-doping also lowers the optimal reaction temperature for maximum Jc and Bc2 by about 30℃
- Ti-doped RRP 108/127 wires reacted at 665℃ provide an overall optimal combination of J_c, RRR and ε_{irr}

(*) N. Cheggour, T. C. Stauffer, W. Starch, P. J. Lee, J. D. Splett, L. F. Goodrich, and A. K. Ghosh, "Precipitous change of the irreversible strain limit with heat treatment temperature in Nb3Sn wires made by the restacked rod process". To be submitted to Appl. Phys. Lett., 2018

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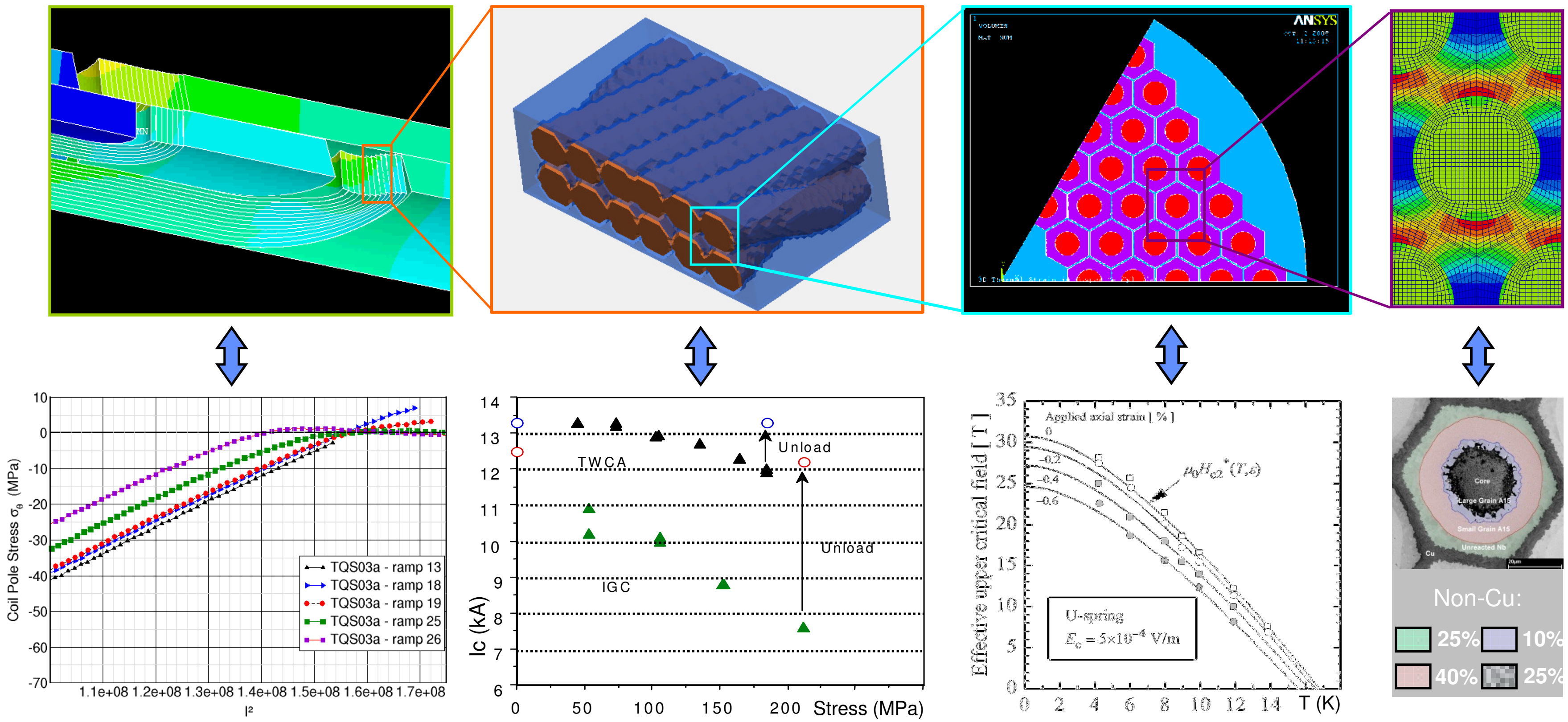
Strain modeling in Nb_3Sn Accelerator Magnets

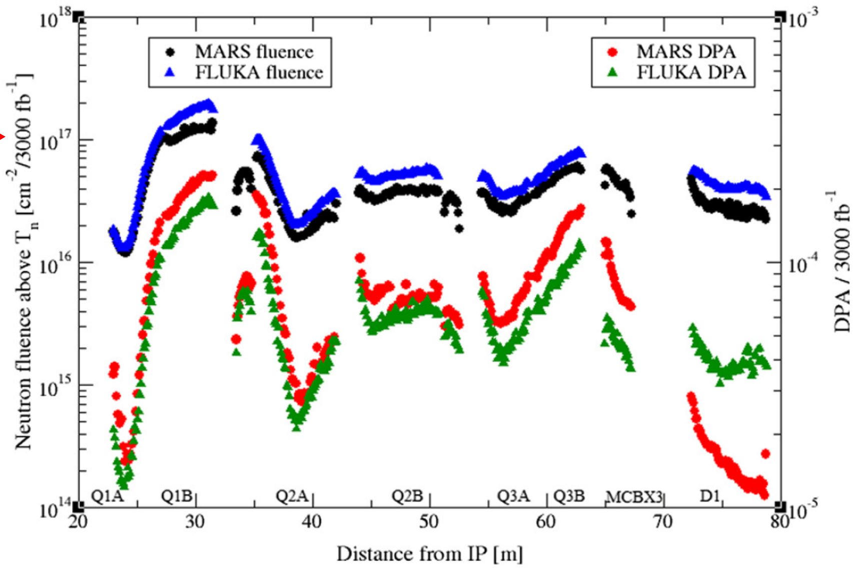
Magnet/Coil **Cable** **Strand** **Filament**



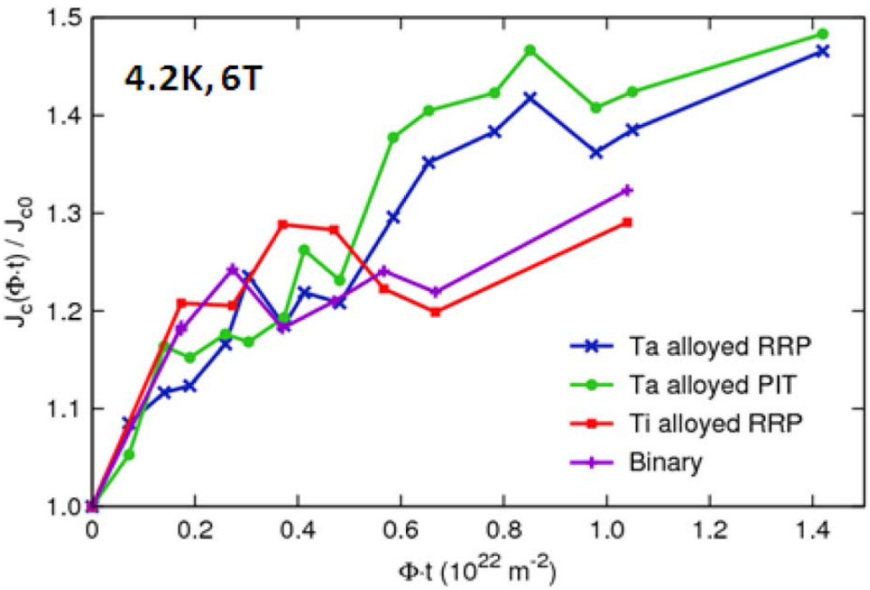
Goal: Understand relations between conductor state at the different scales
Requires developing, validating and correlating models at each scale

Radiation effects on Nb_3Sn conductor J_c

Peak neutron fluence and DPA in HL-LHC IR quadrupole coils *(PRST/AB 18-051001 (2015)*



Normalized critical current density vs. fluence in selected Nb_3Sn wires *(TASC 23-8001404, 2013)*



- Recent results from fast neutron irradiation of Nb_3Sn wires under consideration for HL-LHC IR, including Ti-doped RRP 108/127 selected for MQXFA
- All wires show J_c *enhancement* by 20-40% at the highest fluence reached in the experiment (in the range of 1-1.4 10^{22} m^{-2})
- Earlier studies showed *less favorable results for ternary material* with J_c enhancement up to 0.5 10^{22} m^{-2} and degradation at $1 \cdot 10^{22}$ m^{-2} (binary results are more consistent)
- Peak fluence in HL-LHC IR Quadrupole coils is <0.3 10^{22} m^{-2} at 4000 fb^{-1}

TQ Model Quadrupoles

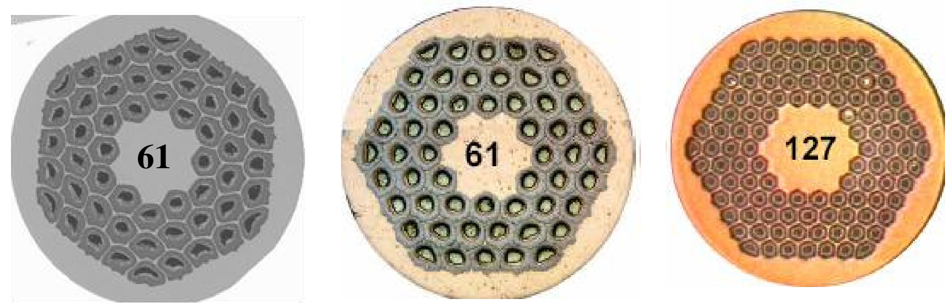
Conductor:

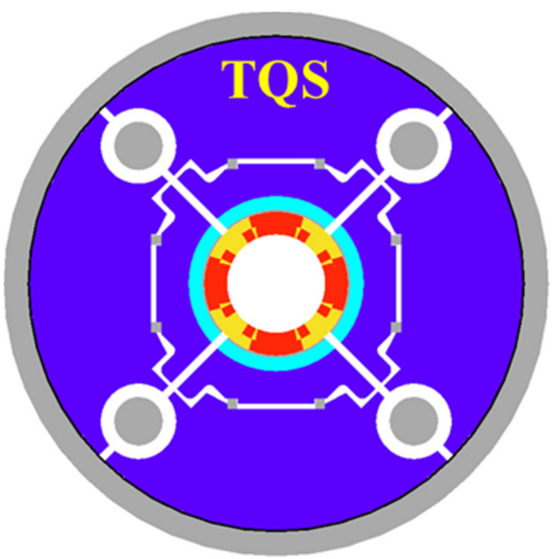
- TQ01: OST MJR 54/61
- TQ02: OST RRP 54/61
- TQ03: OST RRP 108/127

Structure:

- <u>TQS</u> - shell-based
- TQC - collar based

TQ01	**TQ02**	**TQ03**
OST-MJR 54/61	*OST-RRP 54/61*	*OST-RRP 108/127*



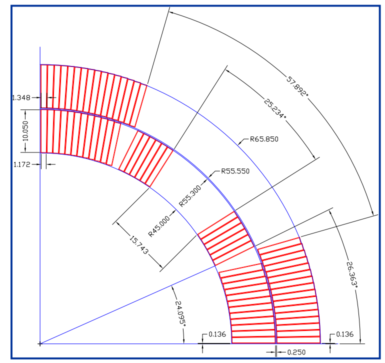


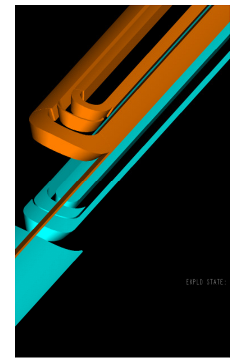
Parameter	Unit	Value
Strand diameter	mm	0.7
No. strands		27
Cable width	mm	10.06
Cable thickness	mm	1.26
Insulation thickness	mm	0.125
Coil aperture	mm	90
No. turns per quadrant (L1, L2)		18, 16
Shell OD	mm	500
Short sample current (4.3K, 1.9K)	kA	13.2, 14.5
Conductor peak field at SSL (4.3K, 1.9K)	T	11.96, 13.02

Coil fabrication process

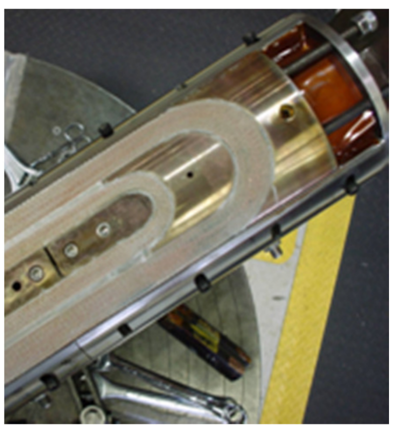
Detailed analysis and selection among coil fabrication processes developed at different Labs started during the TQ program and continued in LQ and HQ

- Cable and insulation
- Design of end parts
- Coil curing process
- Reaction tooling
- Instrumentation/heater traces
- Strain gauge installation





Winding & curing (FNAL - all coils)



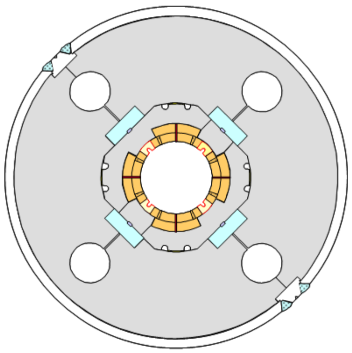
Reaction & potting (LBNL - all coils)

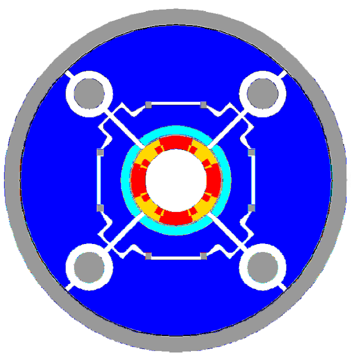
R. Bossert, S. Caspi, D. Dietderich, P. Ferracin, R. Hafalia, R. Hannaford, V. Kashikhin, A. Lietzke, I. Novitski, A. Zlobin et al.

Mechanical design comparison and selection

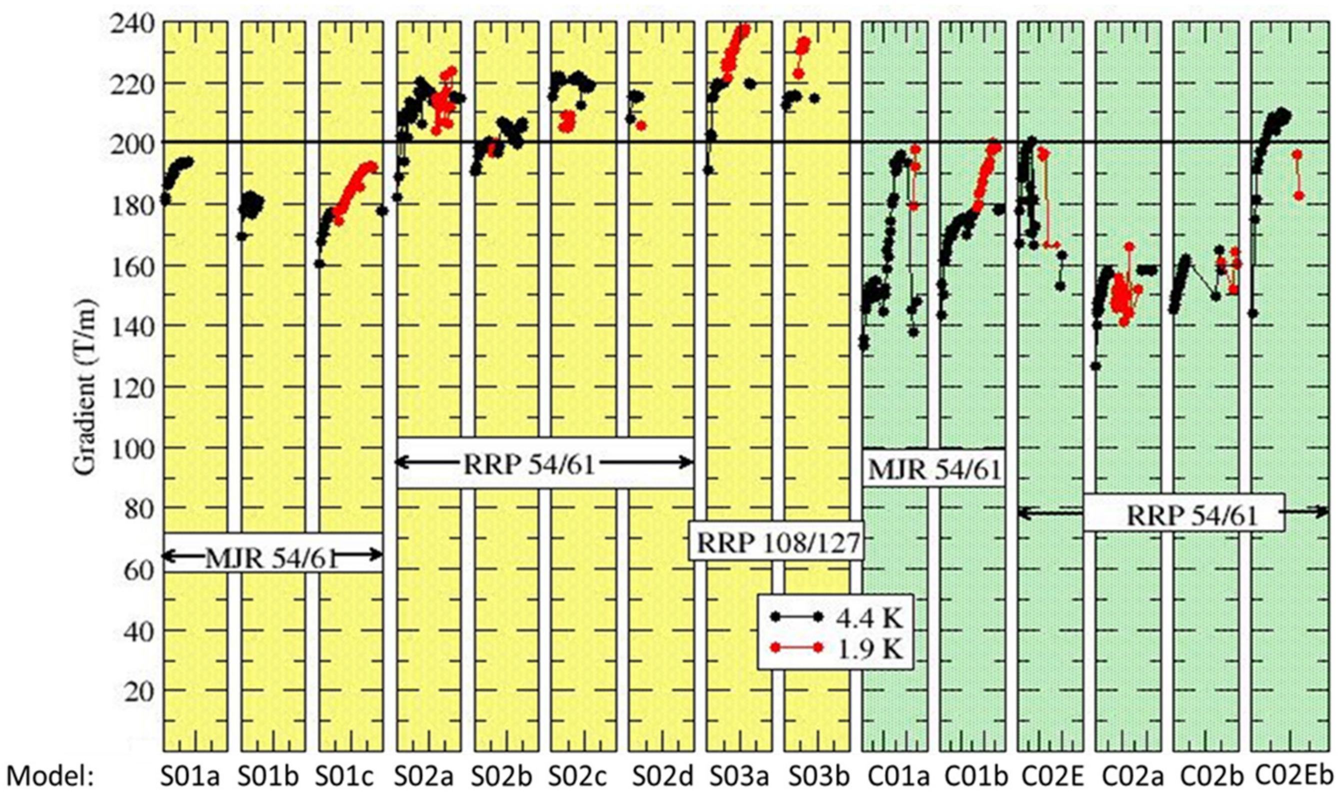
- Two mechanical structures were developed for the TQ coils and their performance was compared in a series of 15 tests
- Both structures surpassed the target gradient of 200 T/m
- The shell structure was selected and further developed in LQ and HQ

TQC (collar-based)

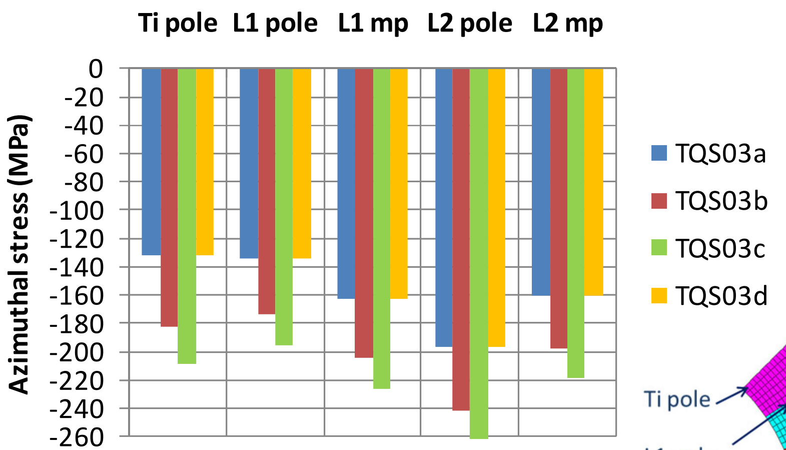




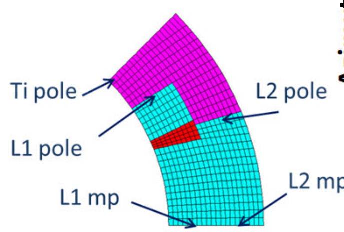
TQS (shell-based)

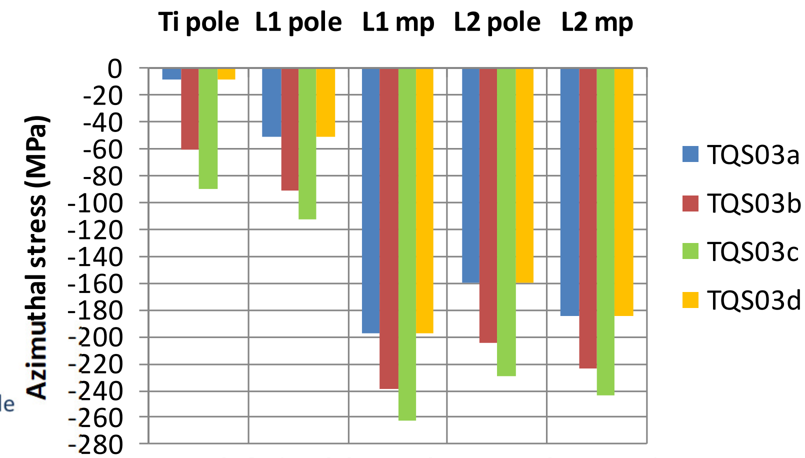


TQS03 loading history and FEA analysis

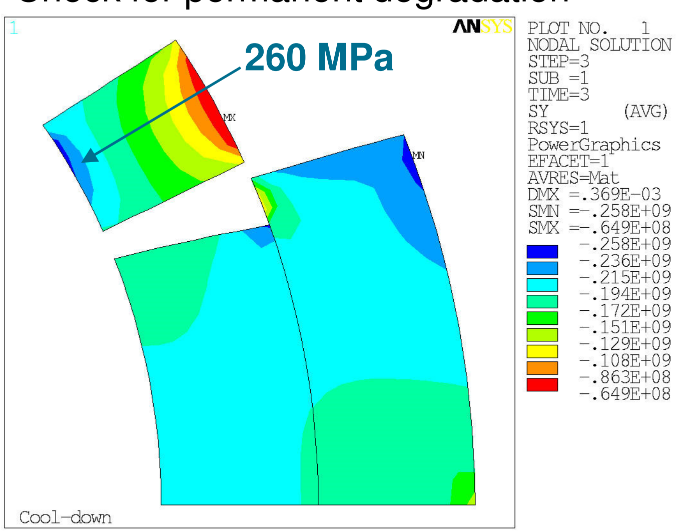


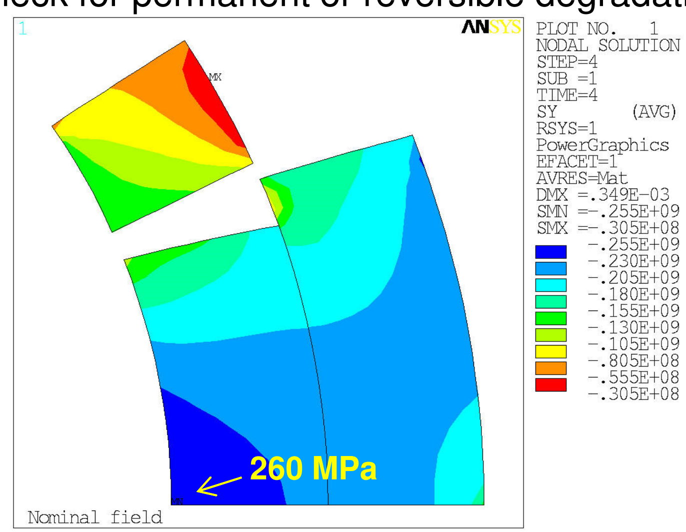
Cold, before powering
Check for permanent degradation





12 kA (achieved quench level)
Check for permanent or reversible degradation

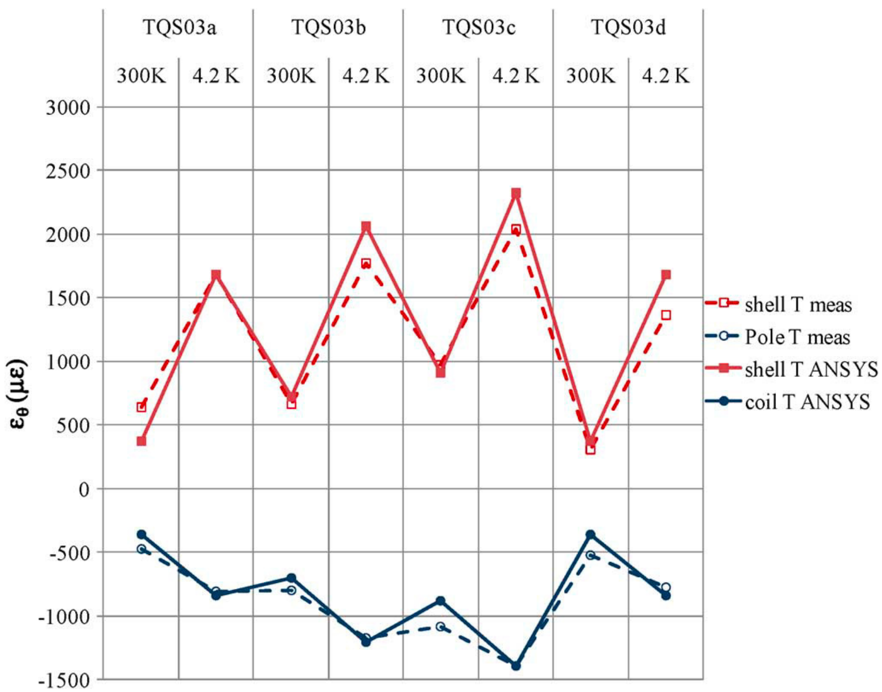


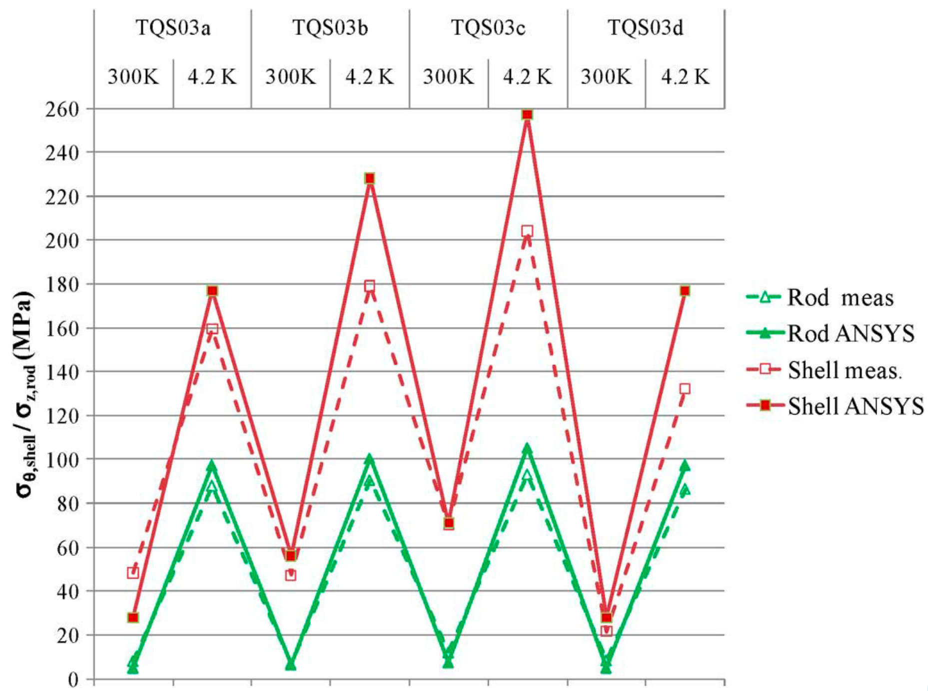


Ref: H. Felice et al., IEEE Trans. Appl. Supercond., vol. 21, no. 3, June 2011.

Validation of TQS03 FEA results

- Based on a comparison with strain gauge measurements at critical locations
  - External shell, axial rods and coil poles
- Required for each individual magnet and test

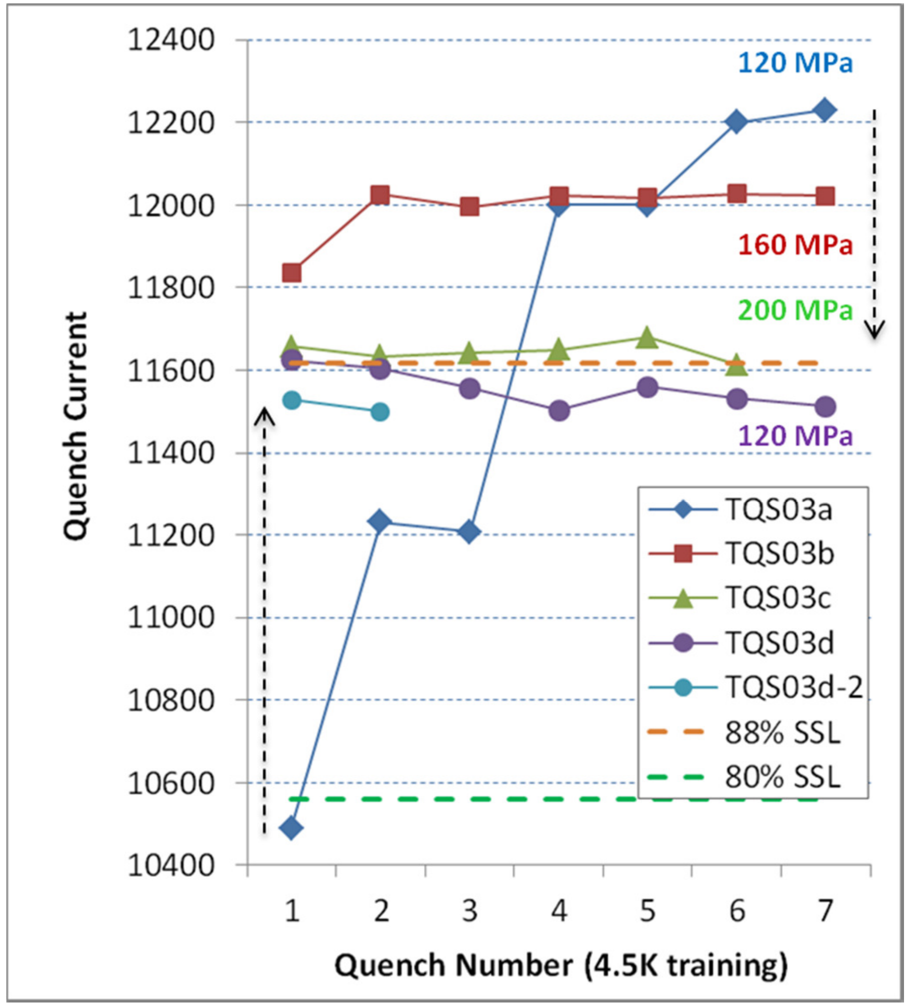




Ref: H. Felice et al., IEEE Trans. Appl. Supercond., vol. 21, no. 3, June 2011.

Pre-load optimization and stress limits

- Balance speed of training and consistent plateau after thermal cycle vs. degradation
- Four tests performed at CERN in TQS03 models with different pre-load
- Increasing pre-load in a/b/c (pole ave.120/160/200 MPa) gives more stable but lower plateau (93/91/88%)
- Degradation is permanent: TQS03d with lower pre-load does not recover initial level
- Good performance in a broad range of coil stress with peak (calculated) up to 240 MPa



H. Bajas, M. Bajko, S. Caspi, H. Felice, P. Ferracin, R. Hafalia, R. Hannaford, J.C. Perez et. al

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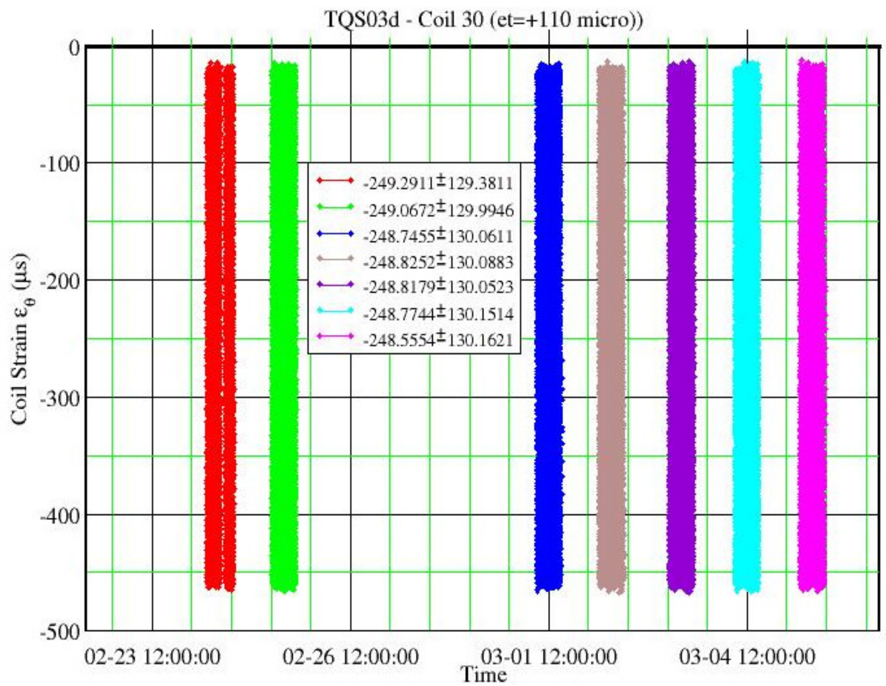
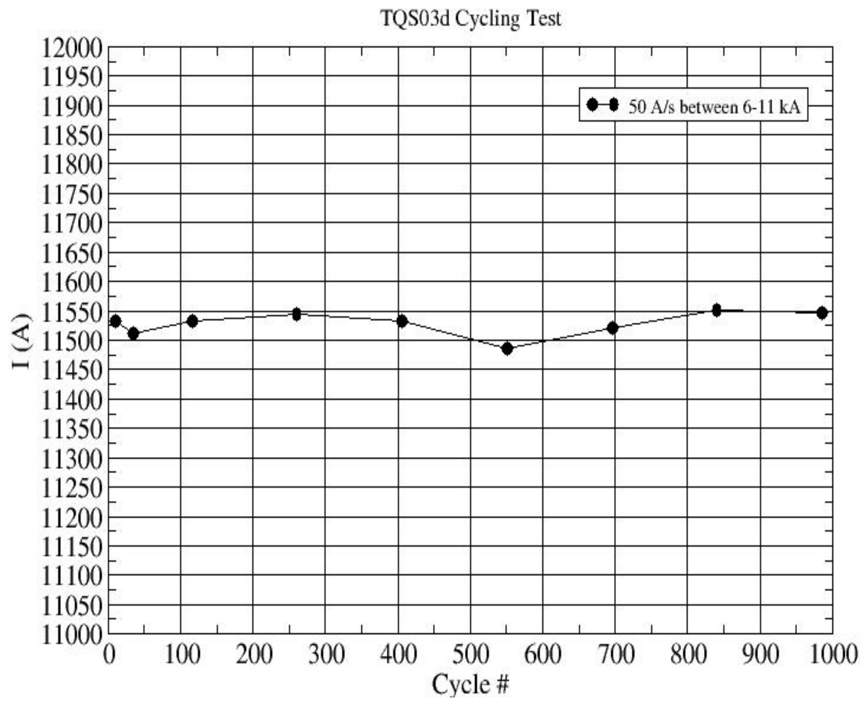
Cycling test to assess long-term degradation

- Cycling test was carried out at CERN using magnet TQS03d
- Performed 1000 cycles with control quenches every ~150 cycles
- No change in mechanical parameters or quench levels

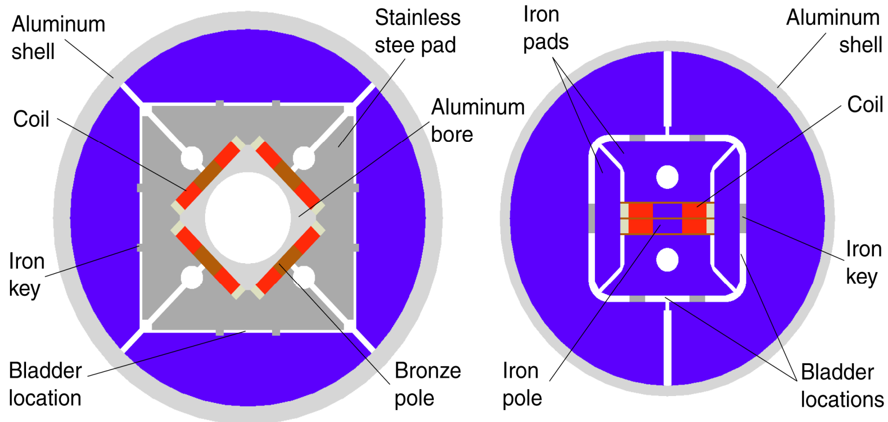




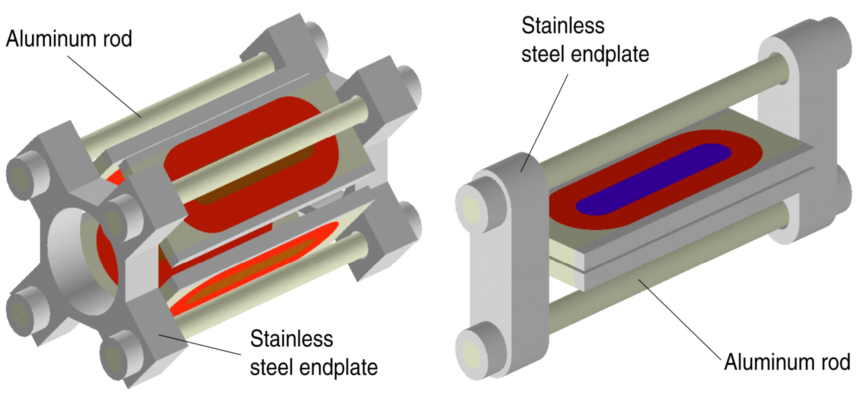
H. Bajas, M. Bajko, G. DeRijk, H. Felice, A. Milanese et. al

Longitudinal strain: SQ and SD studies

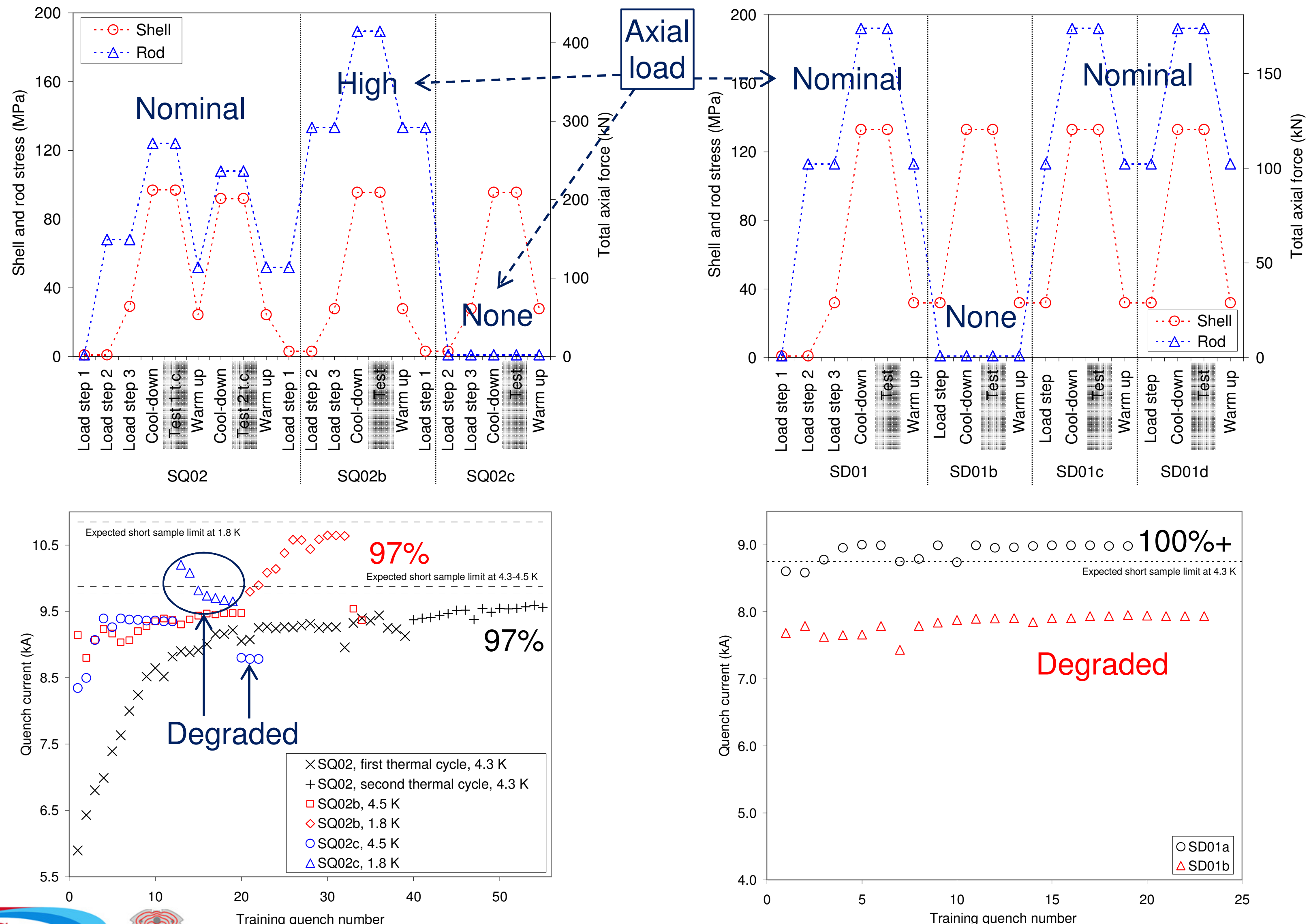
Sub-scale Quadrupole and Dipole SQ/SD: based on 30 cm long racetrack coils



Parameter	Unit	SQ02	SD01
Strand diameter	mm	0.700	0.700
Number of strands		20	20
Cable width (bare)	mm	7.793	7.938
Cable thickness (bare)	mm	1.276	1.280
Cu/Sc ratio		0.89	0.81
Number of turns per layer		21	20
J_c (12 T, 4.2 K)	A/mm²	1870	2334
B_{peak} (4.3 K)	T	11.1	12.5
I_{ss} (4.3 K)	kA	9.9	8.8
F_z per coil @ I_{ss}	kN	83	85



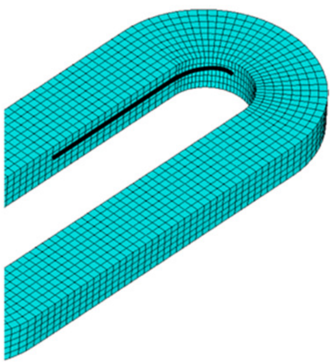
SQ and SD: pre-load history and test results



SQ and SD: Analysis of Longitudinal Strain

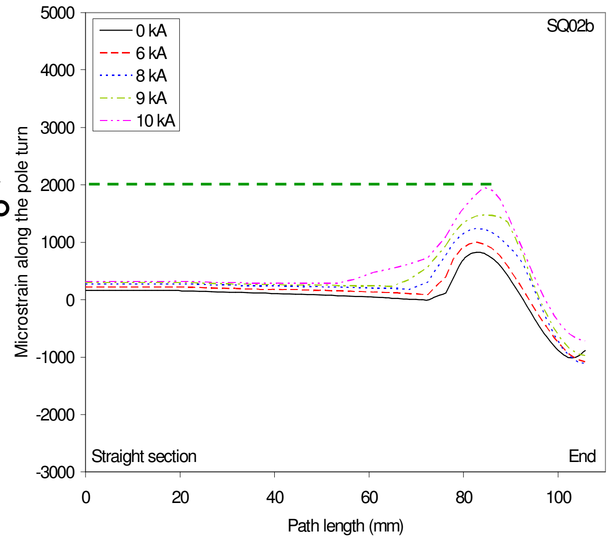
With end load:

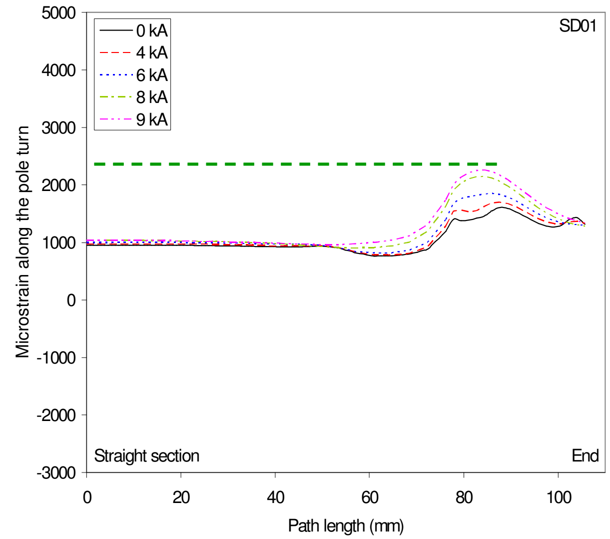
- Axial strain 0.2-0.23%
- 97-100% SSL

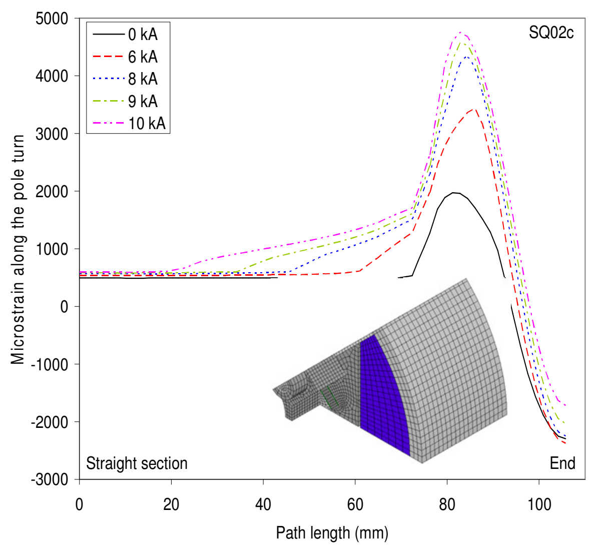


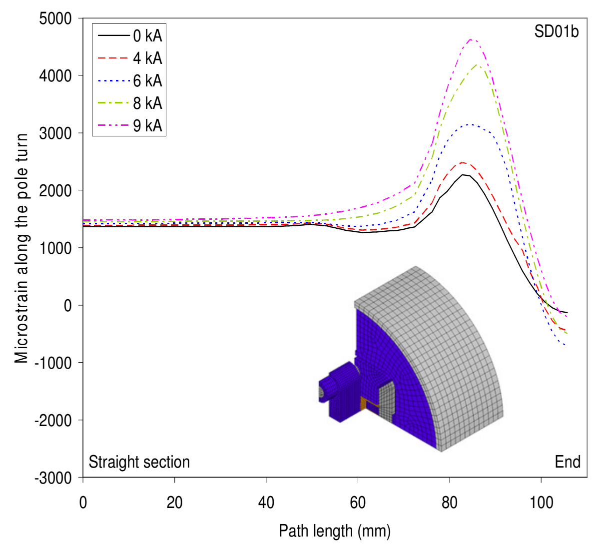
Without end load:

- Axial strain 0.4-0.5%
- Performance degradation

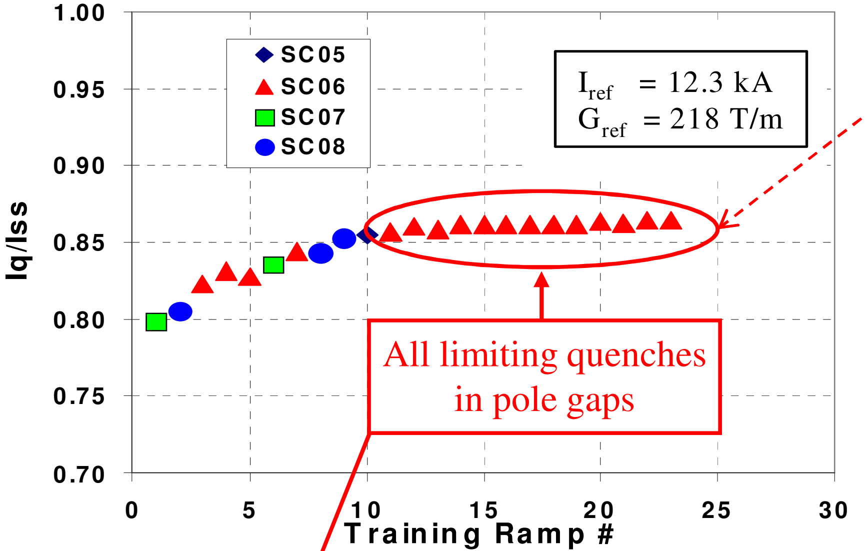


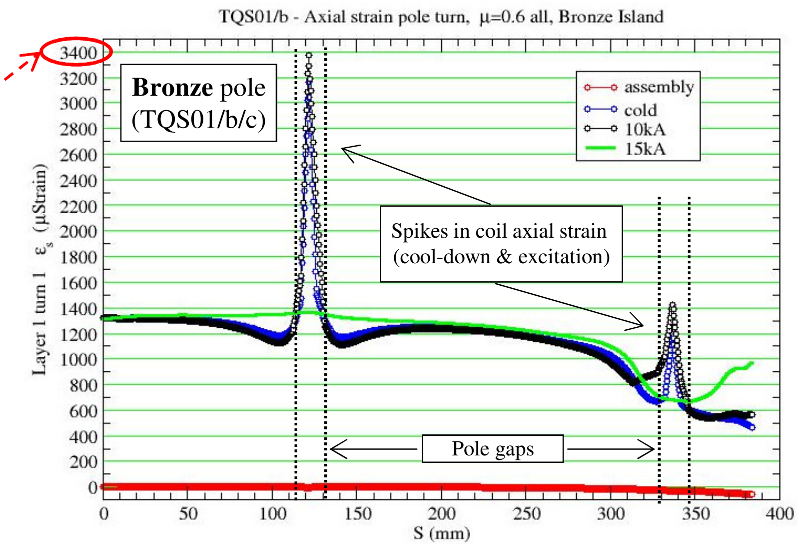


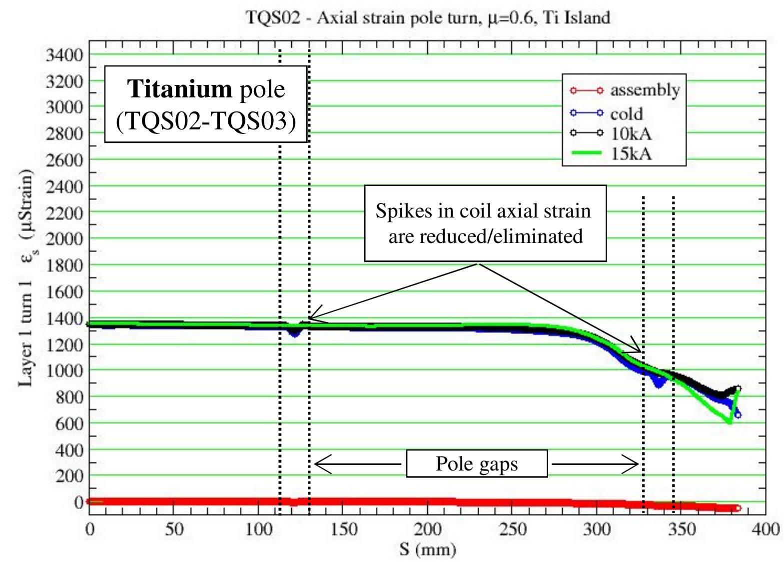


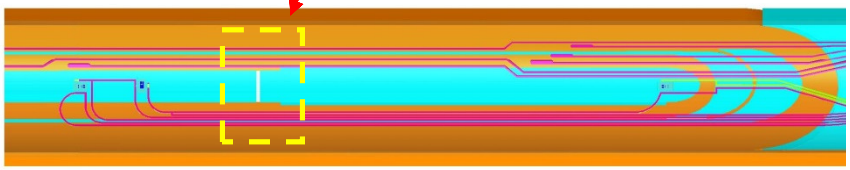


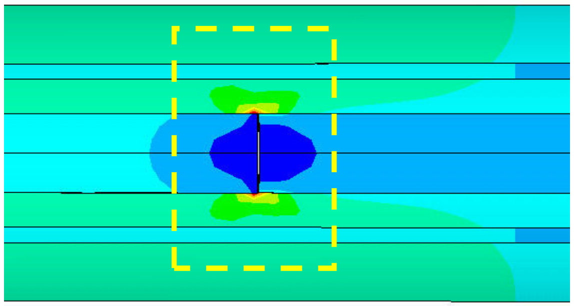
Longitudinal strain: TQ studies

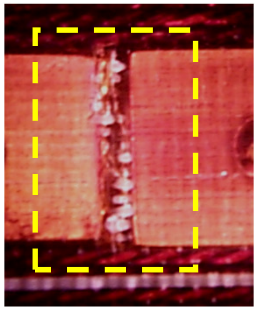






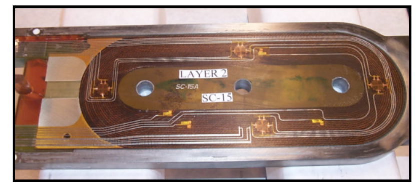


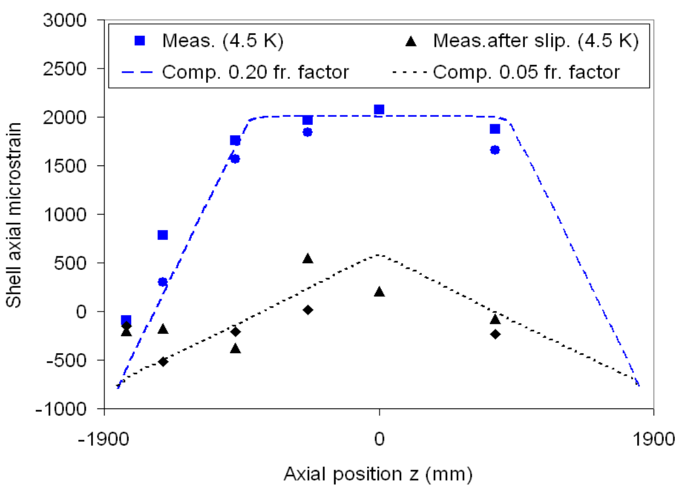


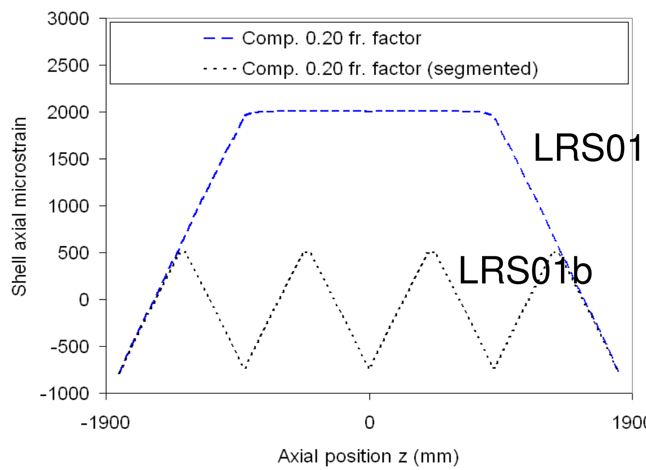


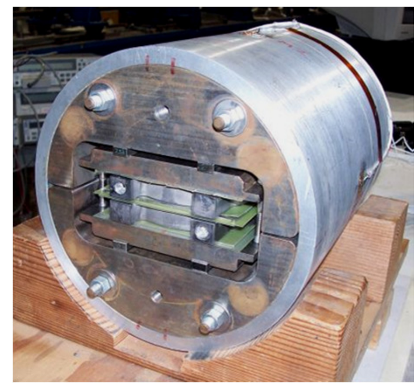
Scale-up to long coils and structures: LR

- The magnet length scale-up was a defining goal of the first R&D phase
- As a first step, the “subscale” coil and structure was extended from 0.3 to 4 m
- The Long Racetrack (LR) magnet successfully achieved 98% SSL in 2006
- Observation of shell-yoke slippage in LR01 led to shell segmentation in LR02
- LR was also used to transfer the wind-and-react coil technology to BNL









G. Ambrosio, M. Anerella, P. Ferracin, R. Hafalia, R. Hannaford, J. Muratore, J. Schmalzle, et al.

US HL-LHC AUP

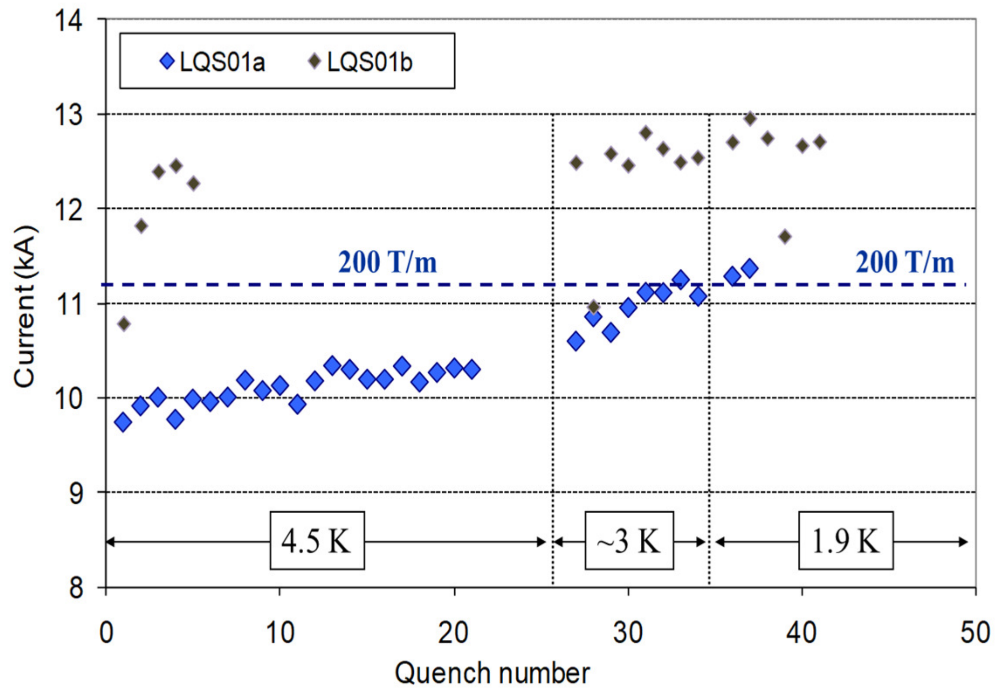
LARP

Scale-up to long coils and structures: LQ

- LARP defining milestone: *reach 200 T/m in 90 mm aperture and 4 m length*
- Based on TQ design, adding coil, tooling and structure features for scale up
- Achieved goal in first test and further improved after radial shim optimization

Coil winding and curing

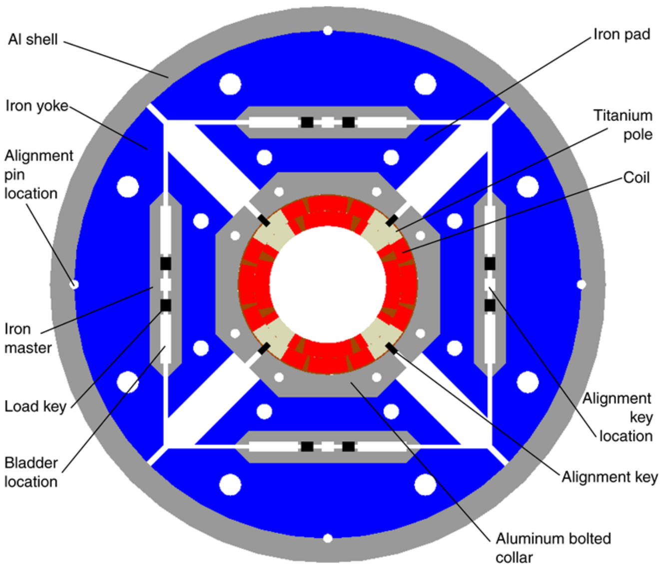
Quench performance of LQS01a and LQS01b



Cool-down test

G. Ambrosio, M. Anerella, R. Bossert, G. Chlachidze, D. Dietderich, H. Felice, P. Ferracin, A. Ghosh, R. Hafalia, R. Hannaford, A. Lietzke, F. Nobrega, J. Schmalzle, P. Wanderer et al.

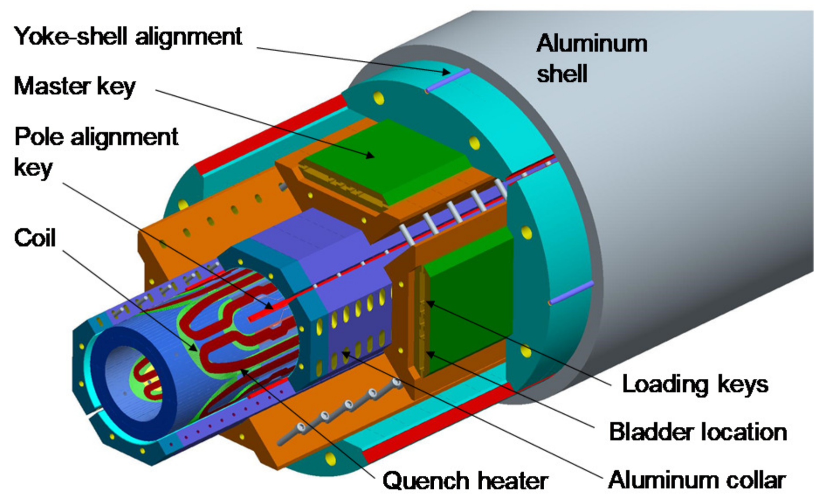
HQ Model Quadrupoles



Parameter	Unit	Value
Strand diameter (HQ01)	mm	0.8
Strand diameter (HQ02-HQ03)	mm	0.778
No. strands		35
Cable width (HQ01)	mm	15.15
Cable width (HQ02-HQ03)	mm	14.8
Cable thickness (HQ01)	mm	1.44
Cable thickness (HQ02-HQ03)	mm	1.37
Coil aperture	mm	120
No. turns per quadrant (L1, L2)		20, 25
Shell OD	mm	500
Short sample current (4.3K, 1.9K)	kA	18.3, 19.9
Conductor peak field at SSL (4.3K, 1.9K)	T	14.1, 15.2

Main features of the HQ series:

- 120 mm aperture
- 14-15 T peak field
- Coil and structure alignment
- Three series of models HQ01, 02, 03



HQ02a and HQ02b Pre-load

HQ02a :

Preload at 300 K:
- $\varepsilon\theta$ shell = 860 $\mu\varepsilon$
- $\sigma\theta$ shell = 66 MPa

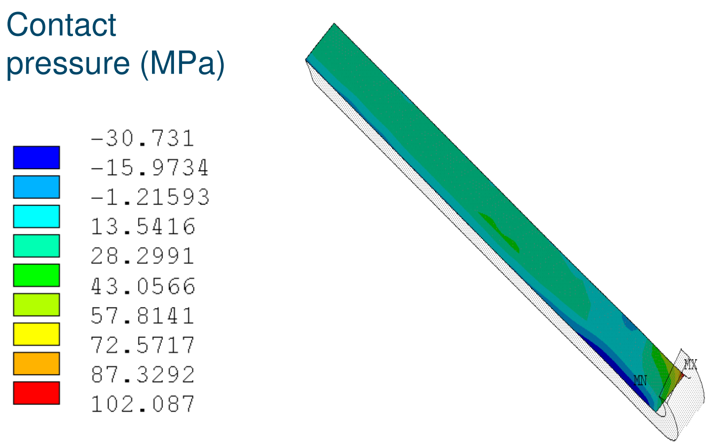
Preload at 4.2 K:
- $\varepsilon\theta$ shell / pole = 1700 $\mu\varepsilon$
- $\sigma\theta$ shell / pole = 164 (+/- 11) MPa

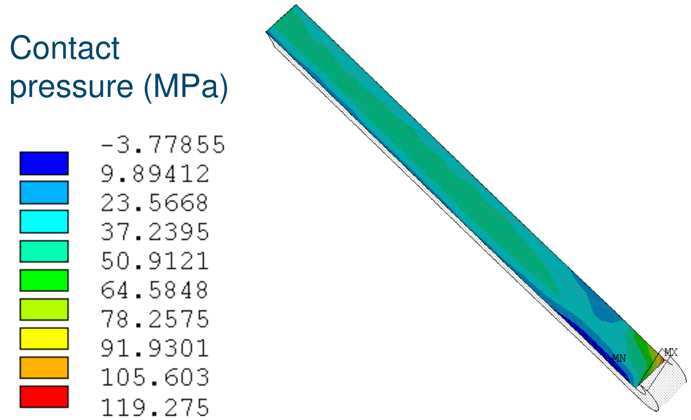
HQ02b :

Preload at 300 K:
- $\varepsilon\theta$ shell = 1270 $\mu\varepsilon$
- $\sigma\theta$ shell = 98 MPa

Preload at 4.2 K:
- $\varepsilon\theta$ shell = 2100 $\mu\varepsilon$
- $\sigma\theta$ shell = 200 MPa

Coil-pole contact pressure at 195 T/m – 17.3 kA





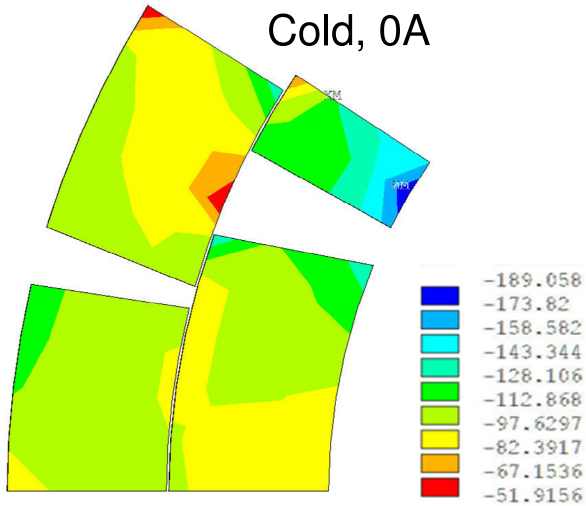
Ref: H. Felice et al., HQ meetings 11/27/13, 9/15/14, https://plone.uslarp.org

HQ02a and HQ02b Coil FEA

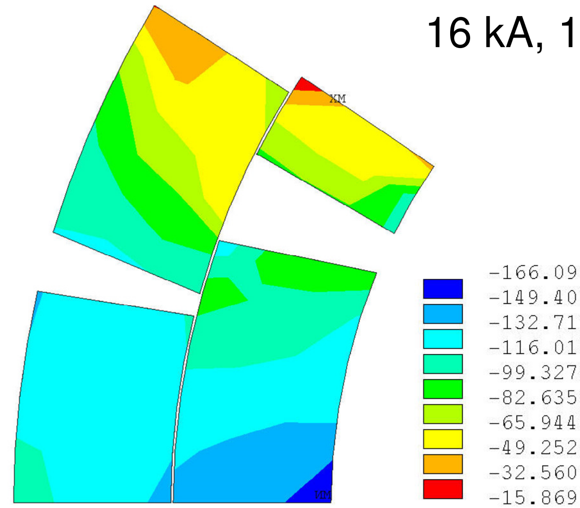
σθ (MPa)

HQ02a:

Cold, 0A



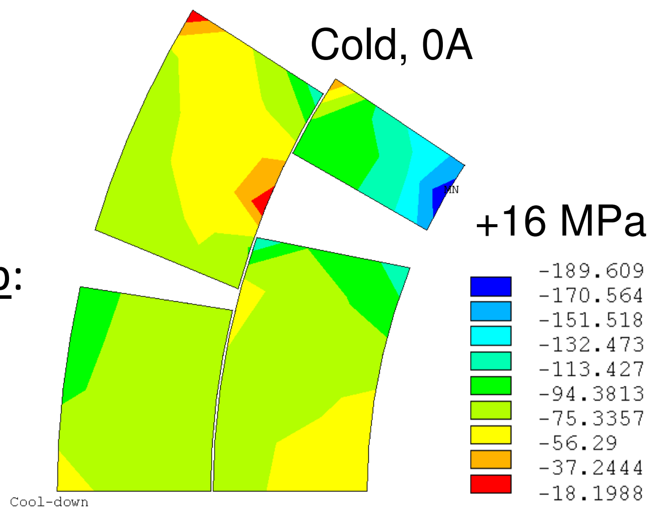
16 kA, 180 T/m



HQ02b:

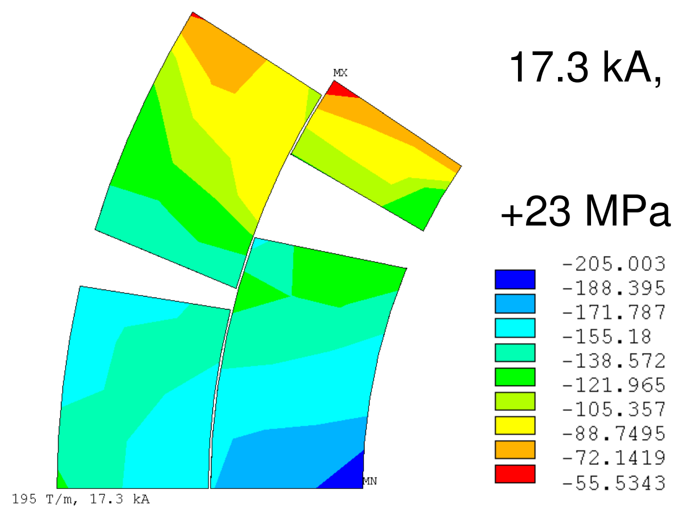
Cold, 0A

+16 MPa



17.3 kA, 195 T/m

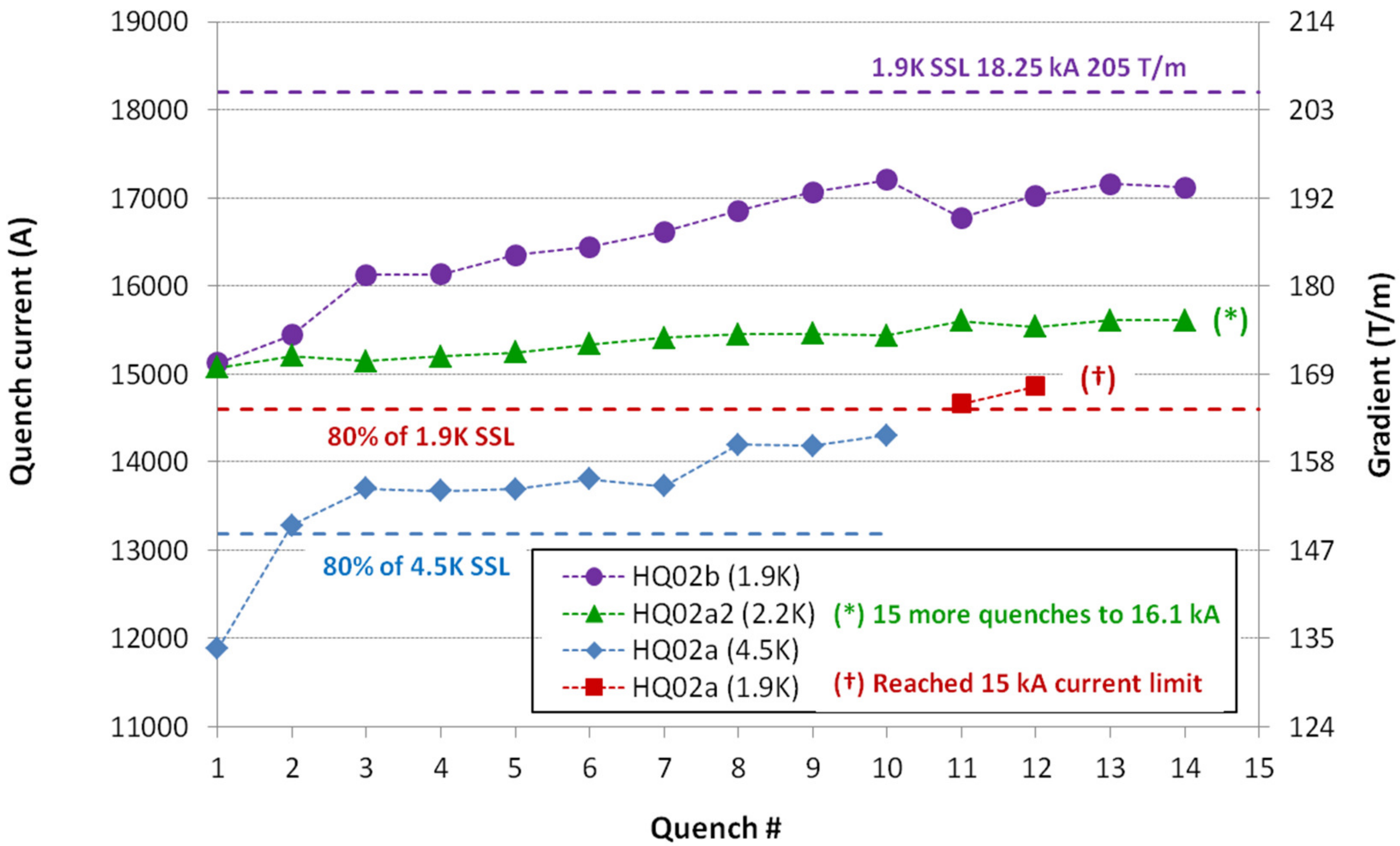
+23 MPa



Ref: H. Felice et al., HQ meetings 11/27/13, 9/15/14, https://plone.uslarp.org

HQ02 Quench Performance

- HQ02a/a2: training rate: 30 A/quench; 98% SSL at 4.5K after training at 1.9K
- HQ02b: training rate: 230 A/quench; 95% SSL at 1.9 K with 200 MPa pre-load

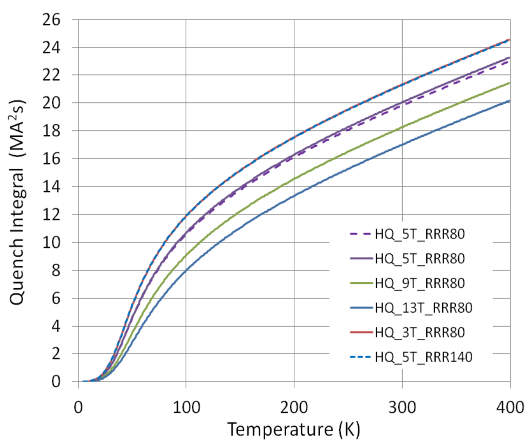


HQ protection limits studies

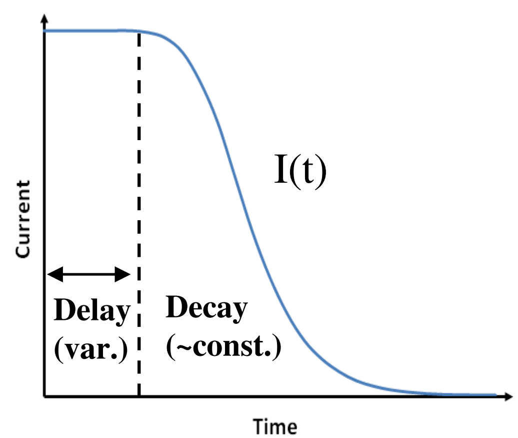
Goal: determine the maximum hot spot temperature before start of permanent degradation

Approach:

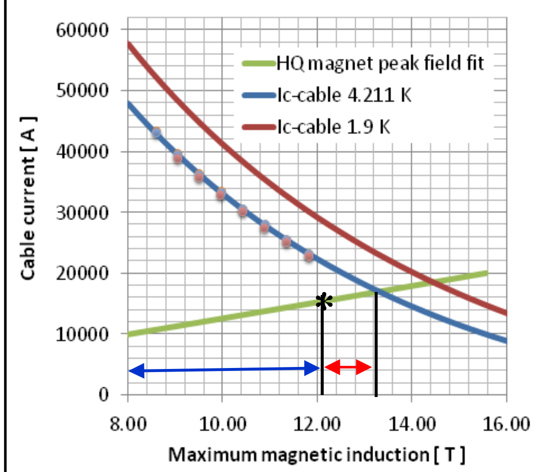
Correlate with key physical quantities affecting magnet performance (temperature, stress etc.) ⇐



Adjust protection system parameters to achieve a controlled increase of the Quench Integral $\int I^2(t)\,dt$

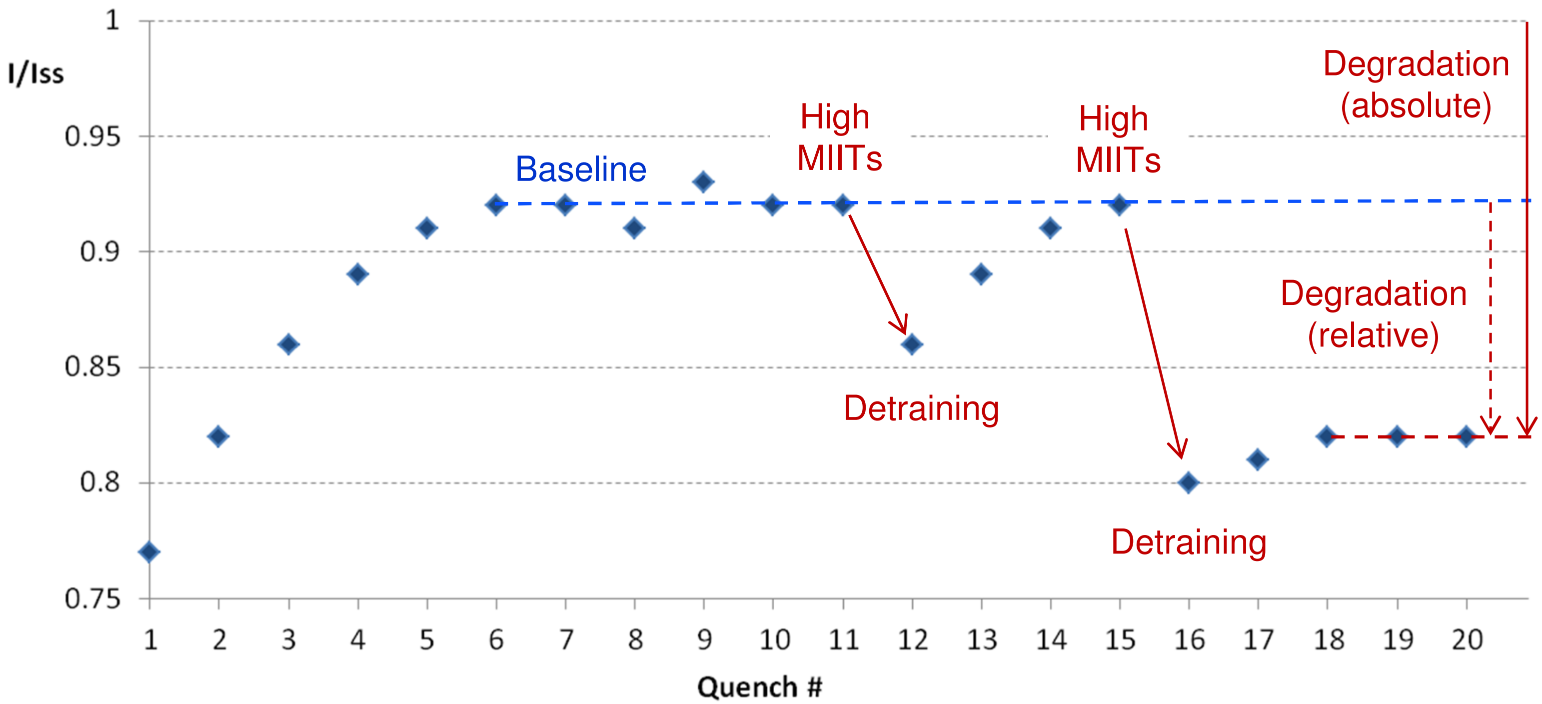


⇒ Correlate with subsequent magnet quench levels (detraining or permanent degradation)



Magnet Performance Characterization

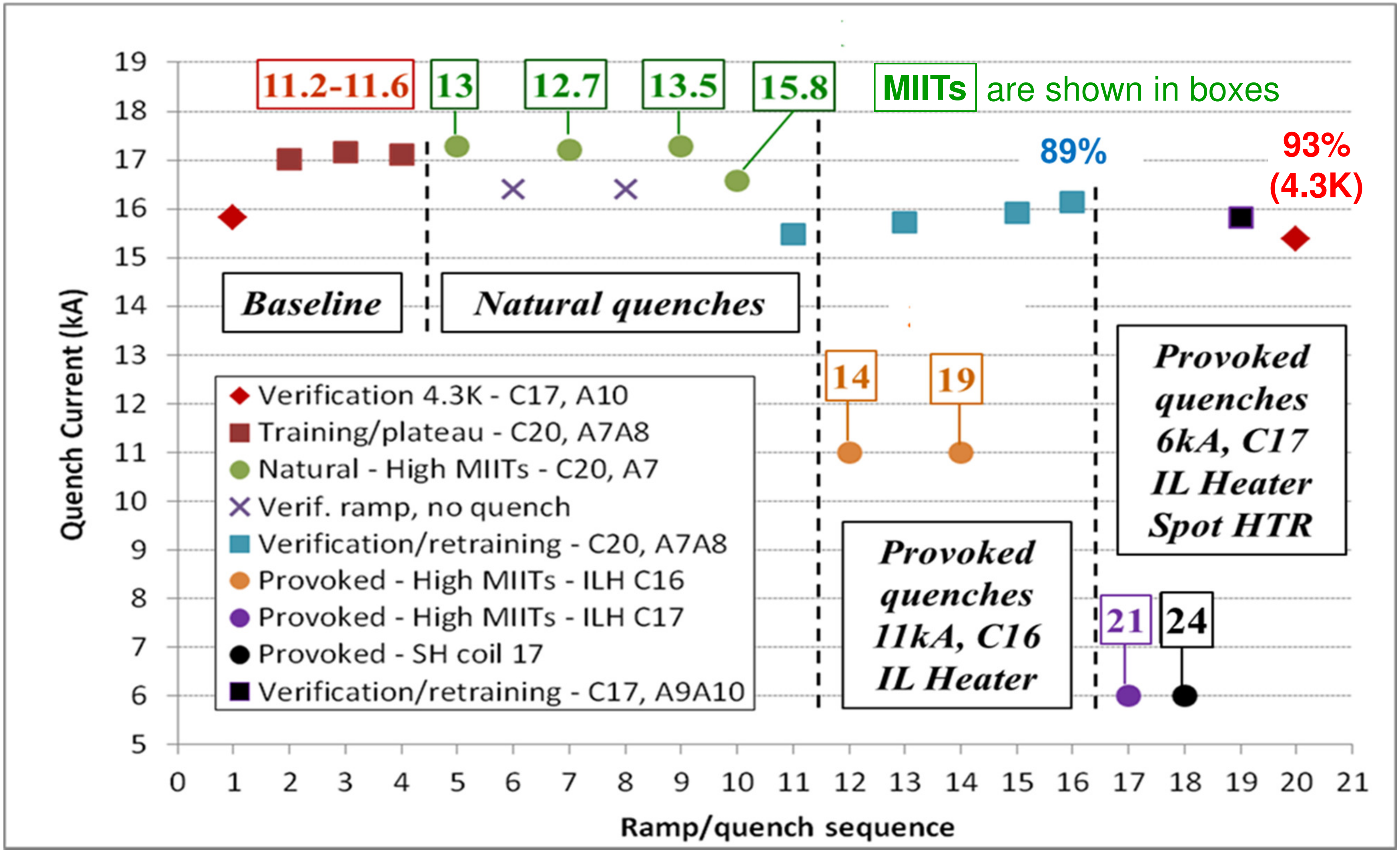
- Similar experiments were performed in the last ~15 years (SM05, TQS01c, HQ01e)
- Performance characterization before and after high MIITs is the key challenge



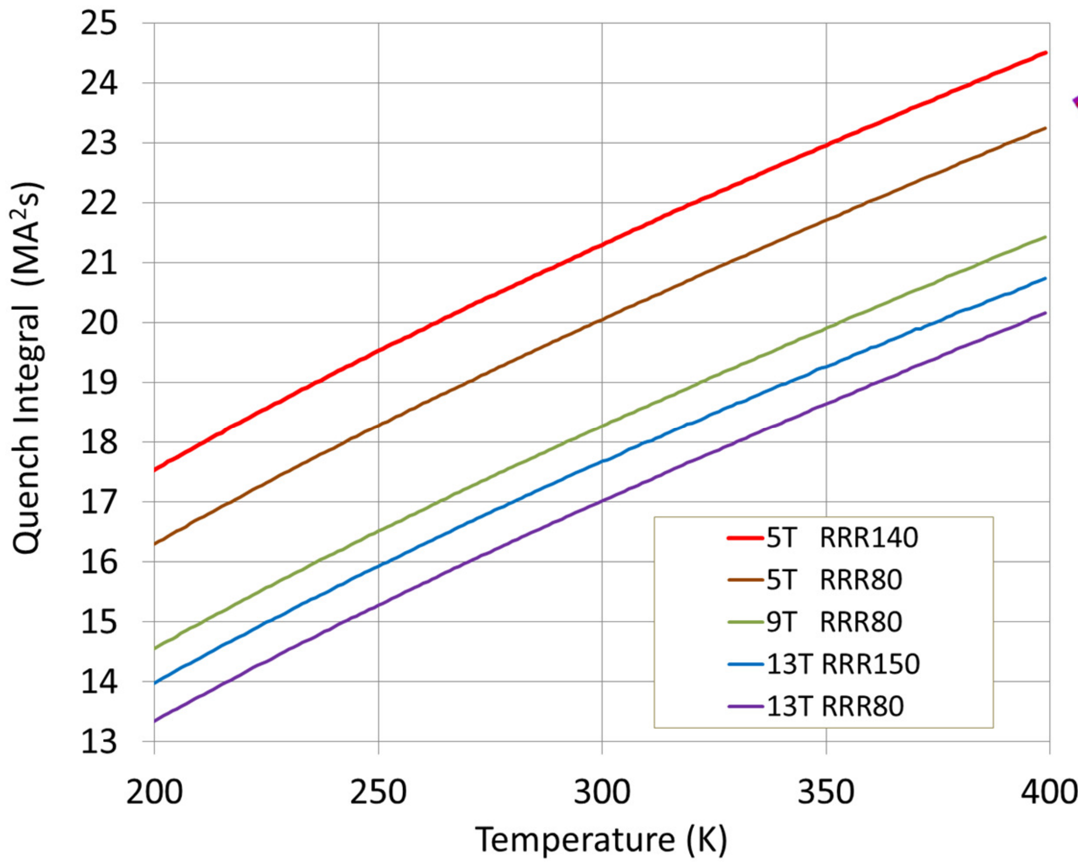
<u>Desired conditions</u>:
- Reproducible quenches at the highest field location (inner layer pole turn) as close as possible to SSL
- High detraining threshold (and fast training/retraining)

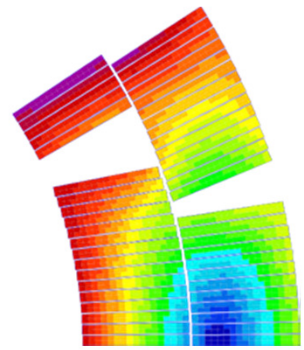
⇔ A PERFECT MAGNET!

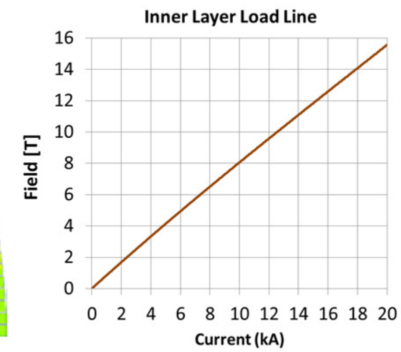
HQ02b Quench Integral study



Quench Integral vs. Temperature







$$\int_0^{\infty}[I(t)]^2\,dt = \nu A^2 \int_{T_0}^{T_{max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)}\,dT$$

$I(t)$: magnet current decay
ν : copper fraction
A : cable area
ρ_{Cu} : copper resistivity
c_p^{ave}: specific heat

- Quench integral vs. temperature calculation by QMIITs & QLASA (T. Salmi, V. Marinozzi)
- Material properties from MATPRO (G. Manfreda et al.) using individual coil parameters
- Estimates based on HQ test data are 20-50 K above adiabatic heat balance *(TASC#4003306)*

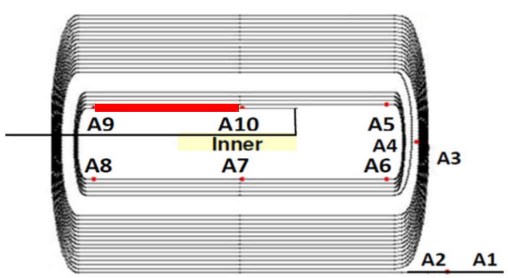
Constraints on permanent degradation

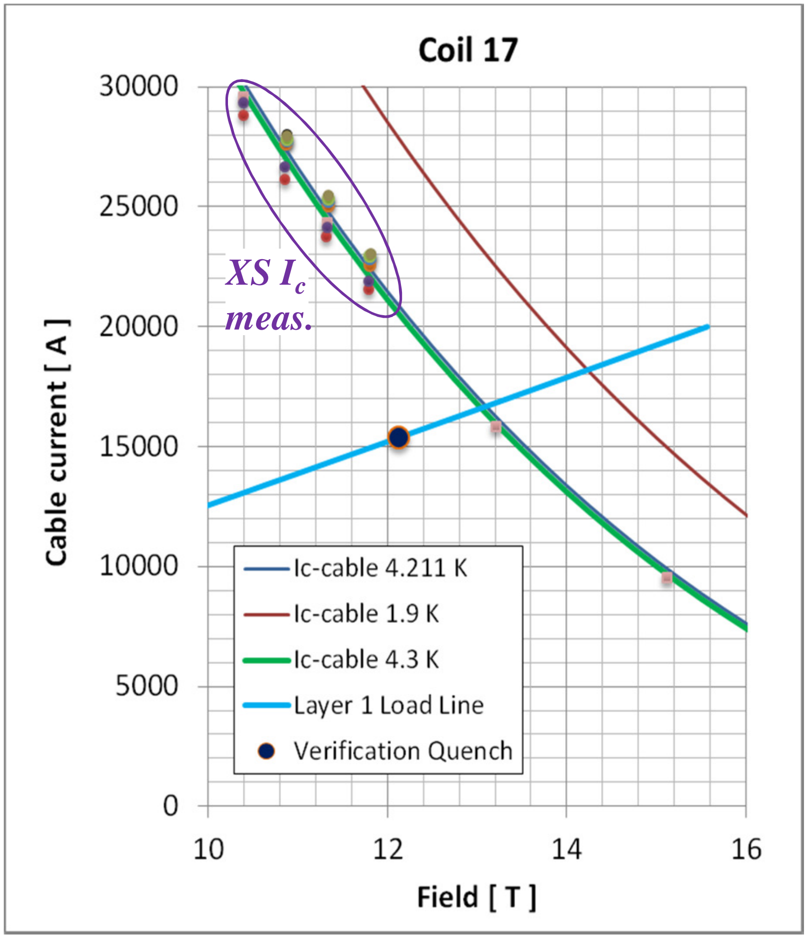
Comparison between 24 MIITs spot heater quench #18 and verification #20 at 4.3K

HQ02b-18	Value
Current	6.0
Coil	17
Segment	A9A10
Field [T]	5.1
Q.I. [MIITs]	24
T_{max} [K]	383

HQ02b-20	Value
Current (kA)	15.38
Coil	17
Quench segment	A9A10
Field A9A10 [T]	12.1
I_q/I_{ss} (4.3K)	0.93
Degradation [%]	<7

- Additional retraining and 4.3K verification would be needed to demonstrate permanent degradation or provide a lower constraint

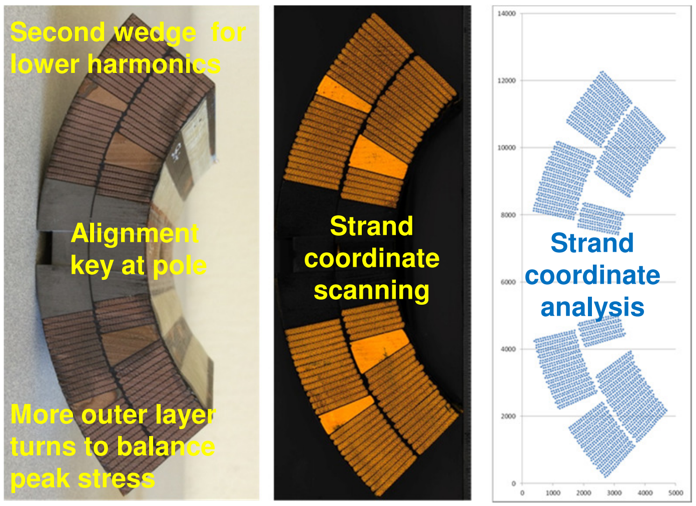




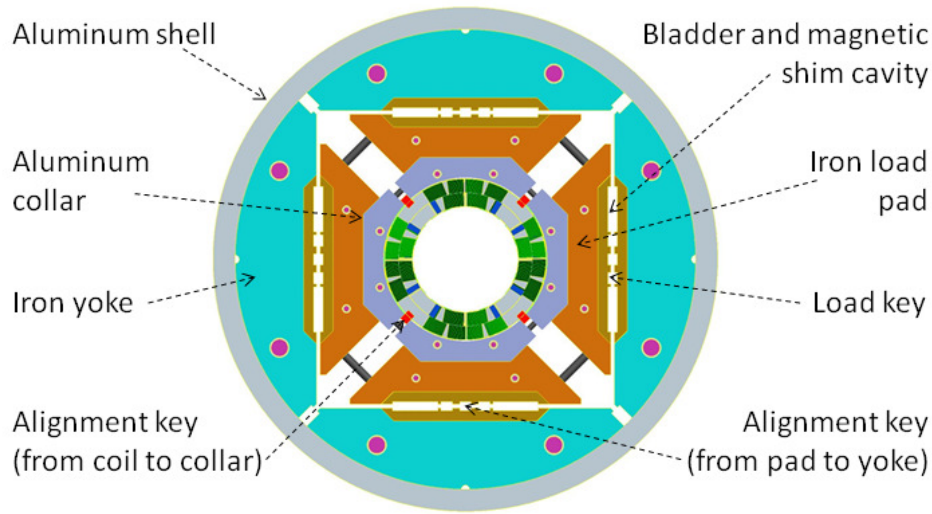
Design and process optimization in HQ and LHQ

- Optimized coil and structure: peak stress at TQ/LQ level despite larger aperture and field
- Introduced features to preserve alignment from coil fabrication to assembly and powering

Coil design



Mechanical structure

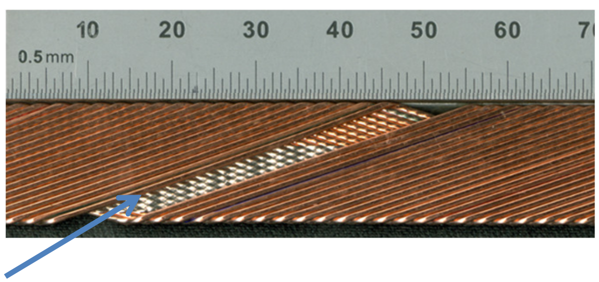


- *Improved coil design and fabrication process for reliability and efficiency in production*:
  - Added axial/transverse space for cable expansion in reaction tooling based on HQ01 experience
  - Electrical integrity: Aluminum oxide coating of coil parts, thicker insulation on cable and heaters
  - New systems and more stringent criteria for electrical QA at all steps of fabrication and test
  - Braided insulation for long unit lengths; new tooling/processes for winding with cored cable

G. Ambrosio, M. Anerella, F. Borgnolutti, R. Bossert, D. Cheng, G. Chlachidze, H. Felice, P. Ferracin, A. Ghosh, M. Marchevsky, F. Nobrega, P. Roy, J. Schmalzle, X. Wang, M. Yu

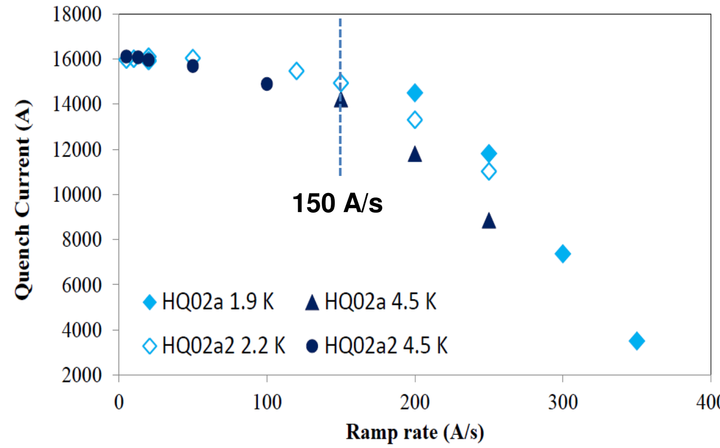
Cable with core for control of dynamic effects

- New cable with stainless steel core in HQ02
  - Partial coverage (80%) to control eddy currents while maintaining current sharing
  - Biased to the thick edge for mechanical stability
- Significant improvement in ramp rate effects:
  - 14.6 kA (80% SSL) up to 150 A/s (1.9K)
  - Safe discharge up to 300 A/s
- One-pass cabling process developed for cored cable cuts cabling effort by more than 50%
- *But*: decreased mechanical stability for winding, requiring more refined tools and procedures

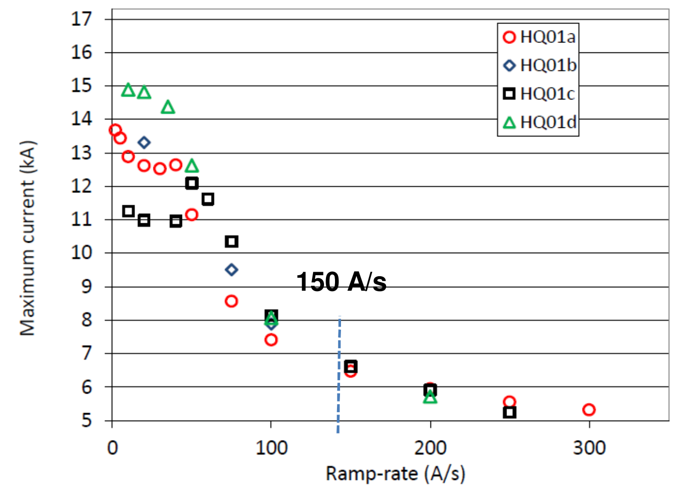


- Stainless steel core biased to the thick edge
- Effective R_c change x10: from 0.1-0.4 μΩ to 2-4 μΩ

HQ02: **15kA @ 150 A/s**



HQ01: **6.5 kA @150 A/s**

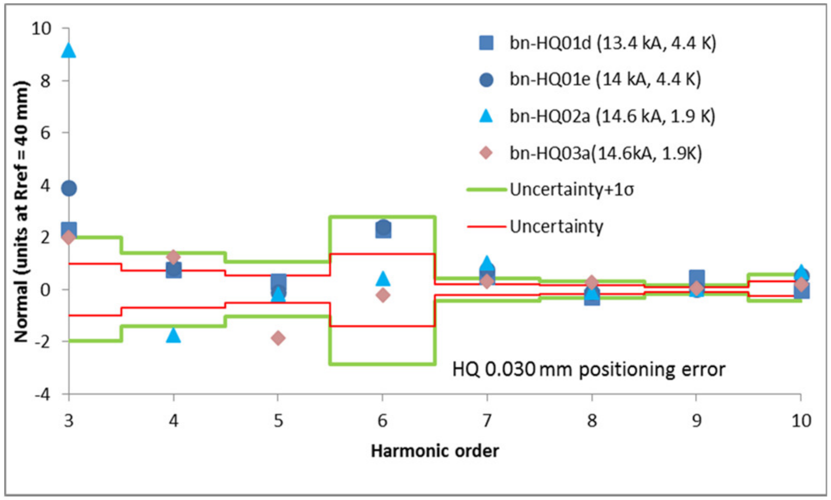


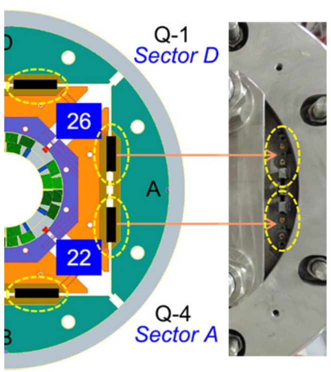
G. Chlachidze, D. Dietderich, J. DiMarco, A. Ghosh, H. Higley, A. Lietzke, N. Liggins, X. Wang et al.

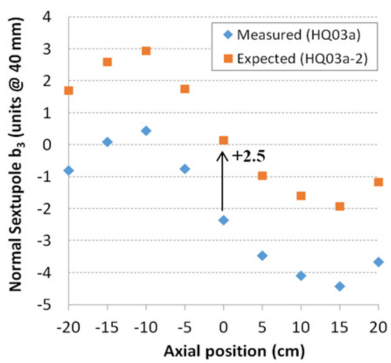
HQ Field Quality and CLIQ Studies

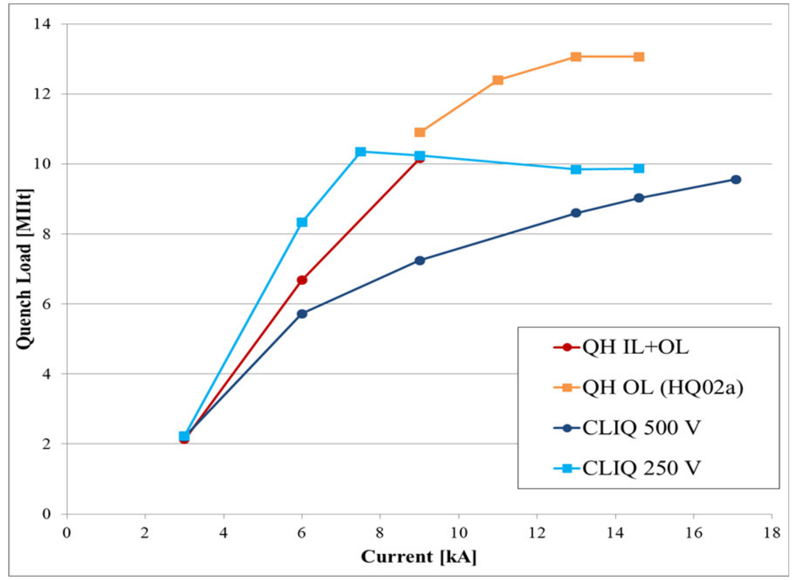
- Field quality: comparison of measurements with as-built calculations and targets
- Tested magnetic shim correction scheme

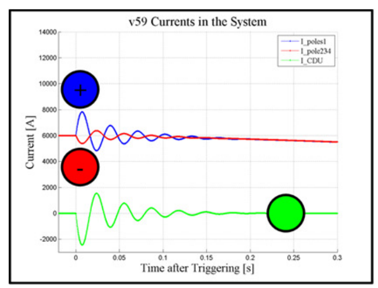
- HQ02b: first test of the CLIQ (Coupling-Loss Induced Quench) system on a Nb_3Sn magnet
- Critical element of MQXF protection strategy

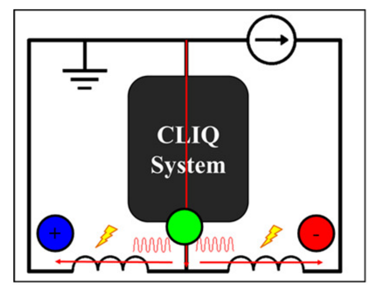










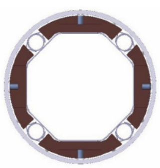


H. Bajas, D. Cheng, G. Chlachidze, V. I. Datskov, V. Desbiolles, J. DiMarco, J. Feuvrier, G. Kirby, M. Marchevsky, E. Ravaioli, X. Wang

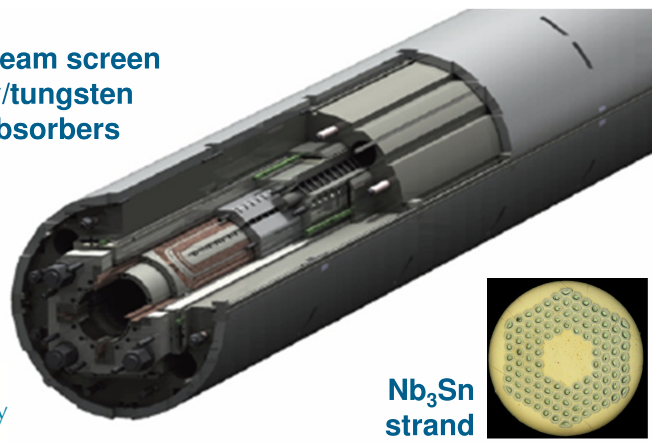
Transition to MQXF

After the selection of 150 mm aperture for the IR, the LARP focus shifted to MQXF design and demonstration

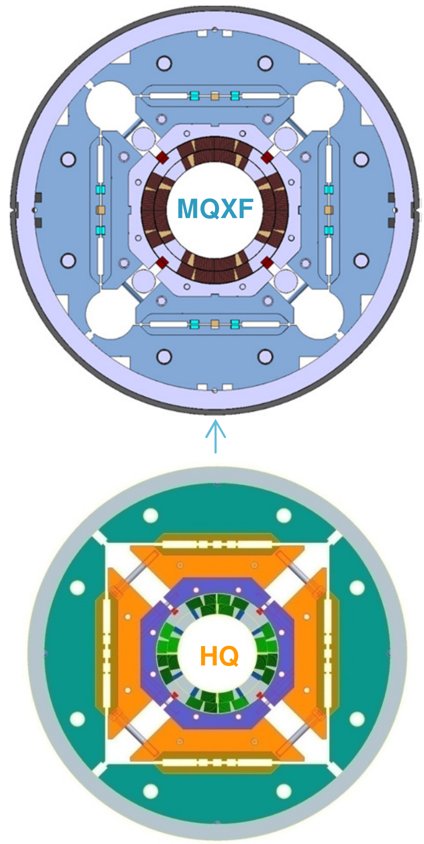
PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at nominal current	T	11.4
Stored energy at nominal	MJ/m	1.2
Peak field at ultimate current	T	12.4



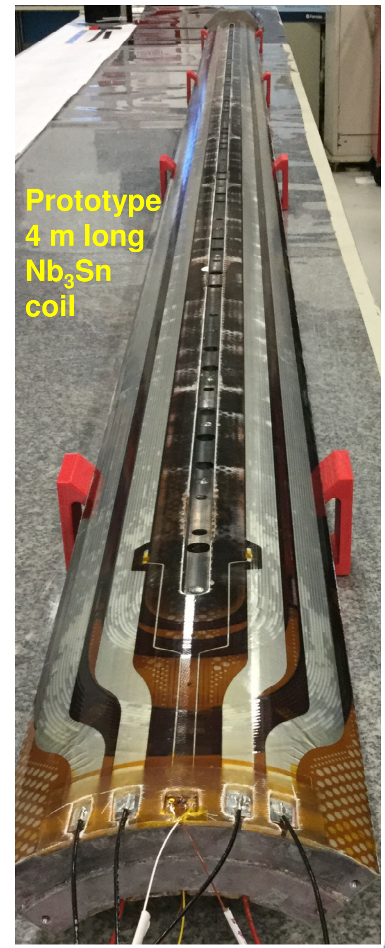
Beam screen w/tungsten absorbers



Nb_3Sn strand



Top: MQXF cross section
Bottom: HQ cross-section



LARP

High Luminosity LHC

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Strand Design Criteria - Summary Table

Parameter	Symbol	Unit	Value
Effective filament diameter	D_{eff}	mm	< 55
Residual Resistivity Ratio (strand)	RRR		>150
Residual Resistivity Ratio (magnet)	RRR		>100
Superconductor composition			Ti-alloyed Nb_3Sn
Nb:Sn atomic ratio			3.6:1
Irreversibility strain	ε_{irr}		0.25%
Reaction temperature		°C	665
Reaction time		h	<50
Stability current margin	I_s/I_{op}		>2
Maximum neutron fluence between anneals		cm^{-2}	$3\ 10^{18}$
Maximum displacements per atom between anneals	DPA		2×10^{-4}

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Cable Design Criteria - Summary Table

Parameter	Unit	Value
Width increase factor(*)		1.02-1.03
Edge compaction	%	85-90
I_c degradation from cabling	%	<5
Cabling process		1-pass
Core coverage		60-80%
Core bias		Major edge

Coil Design Criteria - Summary Table

Parameter	Symbol	Unit	Value
Coil expansion after reaction (width)		%	1.2
Coil expansion after reaction (thickness)		%	4.5
Coil expansion after reaction (length)		%	-0.4 to -0.2
Maximum acceptable localized tension at the coil-pole interface		MPa	<20
Coil azimuthal stress at assembly	σ_θ	MPa	<120
Coil azimuthal stress at cool-down	σ_θ	MPa	<200
Coil azimuthal stress at powering	σ_θ	MPa	<200
Coil longitudinal strain	ε_z	%	<0.2
Maximum acceptable Hot spot temperature	T_{hs}	K	<350

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LARP

Summary

- The LARP Magnet Program has bridged the gap from proof-of-principle tests to LHC IR Quad demonstrators addressing accelerator and production requirements
- The LARP developments resulted in a design approach for Nb_3Sn IR Quadrupoles that has been applied to MQXF
- Based on this experience design criteria have been formulated in terms of acceptable values (ranges) for key parameters
- The design criteria represent a consistent set of parameters that can be simultaneously achieved and result in an optimal choice for the overall magnet performance and cost
- Further verification and optimization is performed for application to MQXFA
  - Initially at the level of individual components: cable, practice coils, etc.
  - Ultimately by magnet fabrication, test and analysis (short models and long prototypes)